Perspectives in Higgs Physics

Marumi Kado

Max Planck Institute for Physics

60th International Meeting on Nuclear Physics

Bormio 20 February 2024

Higgs Physics Broad Landscape

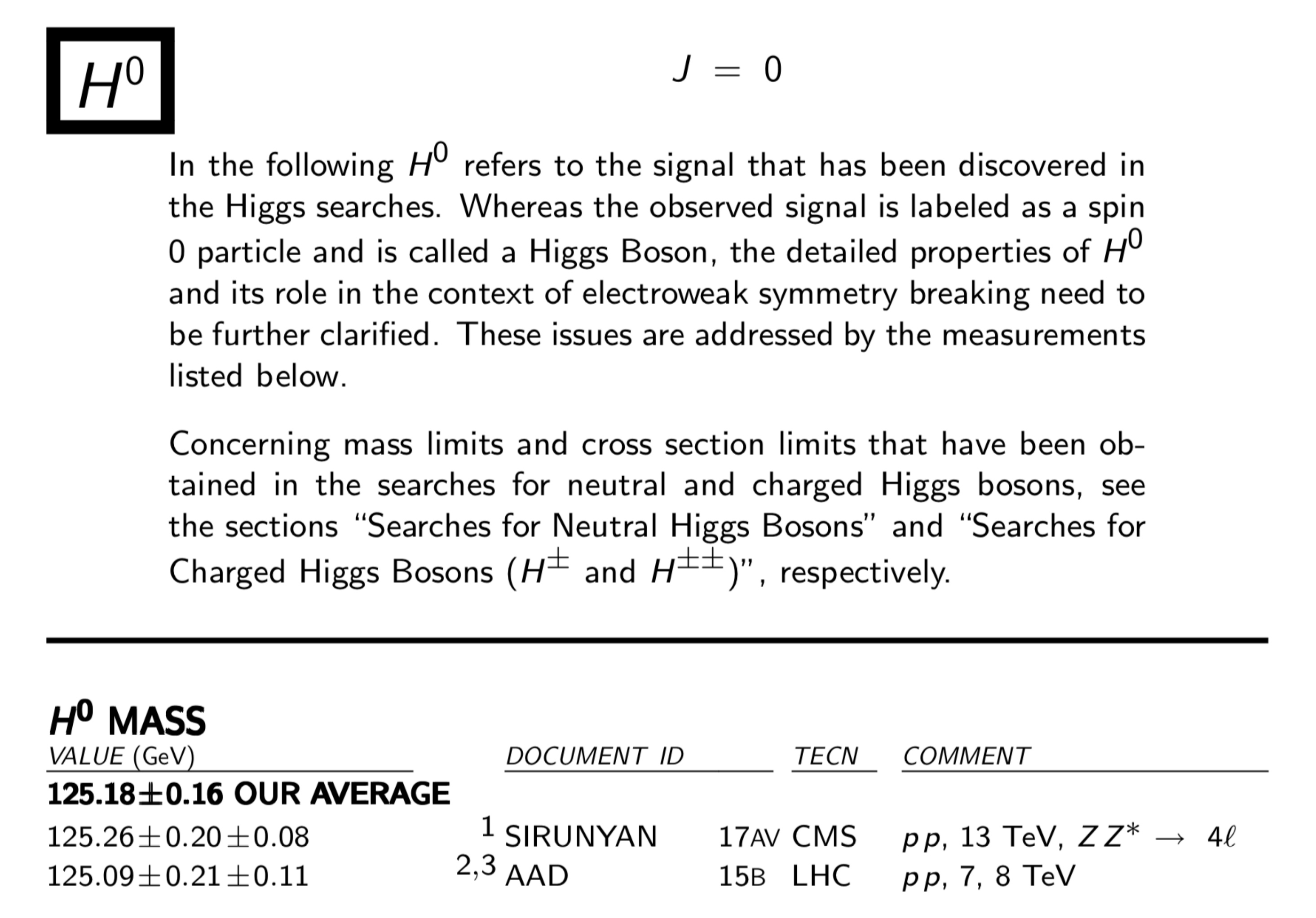
Precision

- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry

Rare Production

- tH (single top and Higgs)
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

The Higgs particle



$\boxed{H^0}$ $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.18±0.16 OUR AVERAGE			
125.26±0.20±0.08	[1] SIRUNYAN 17AV	CMS	pp, 13 TeV, $ZZ^* \rightarrow 4\ell$
125.09±0.21±0.11	[2,3] AAD 15B	LHC	pp, 7, 8 TeV

PDG Listing entry for the Higgs boson

Rare decays

- $Z\gamma, \gamma\gamma*$, Muons $\mu^+\mu^-$
- LFV $\mu\tau, e\tau$
- $J/\Psi\gamma, Z\Upsilon$, WD, $\phi\gamma, \rho\gamma$

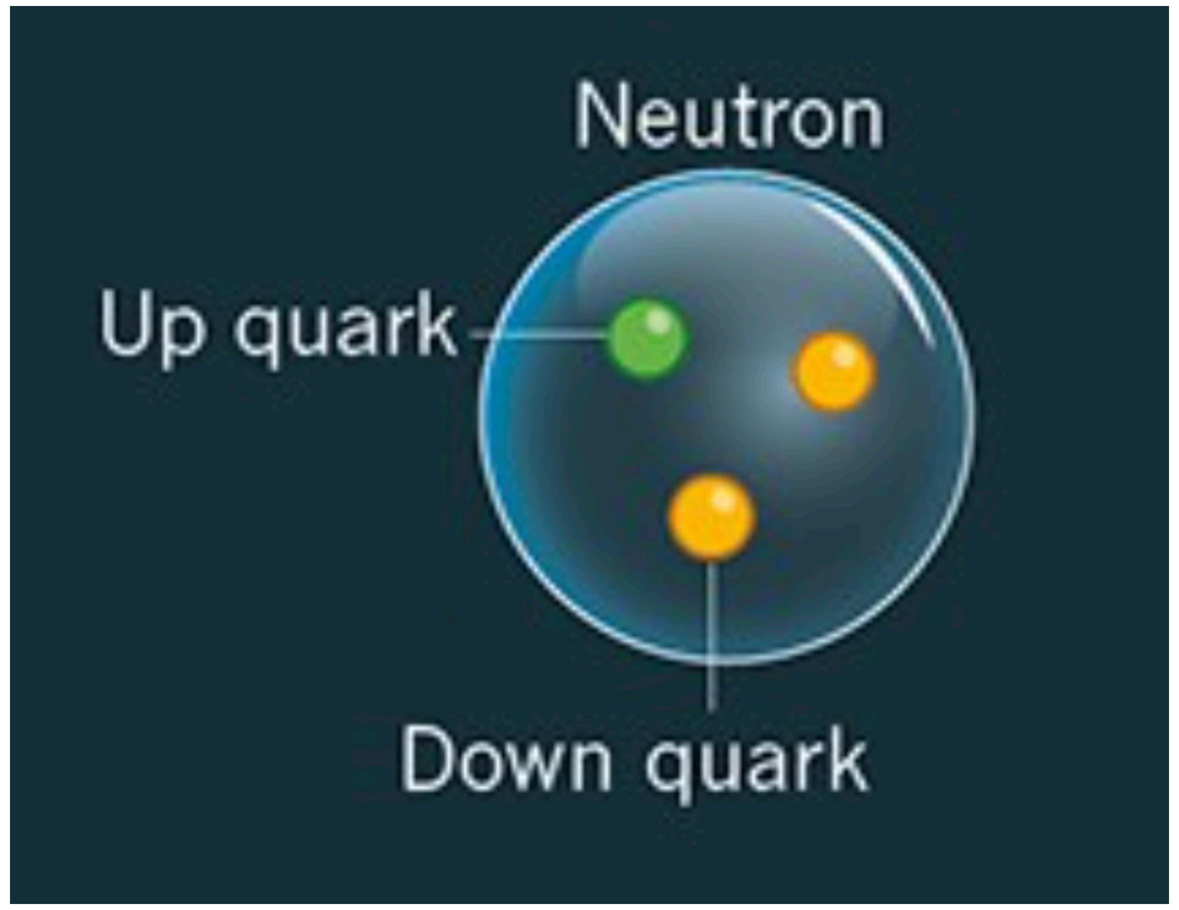
Non minimal Higgs sectors

- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

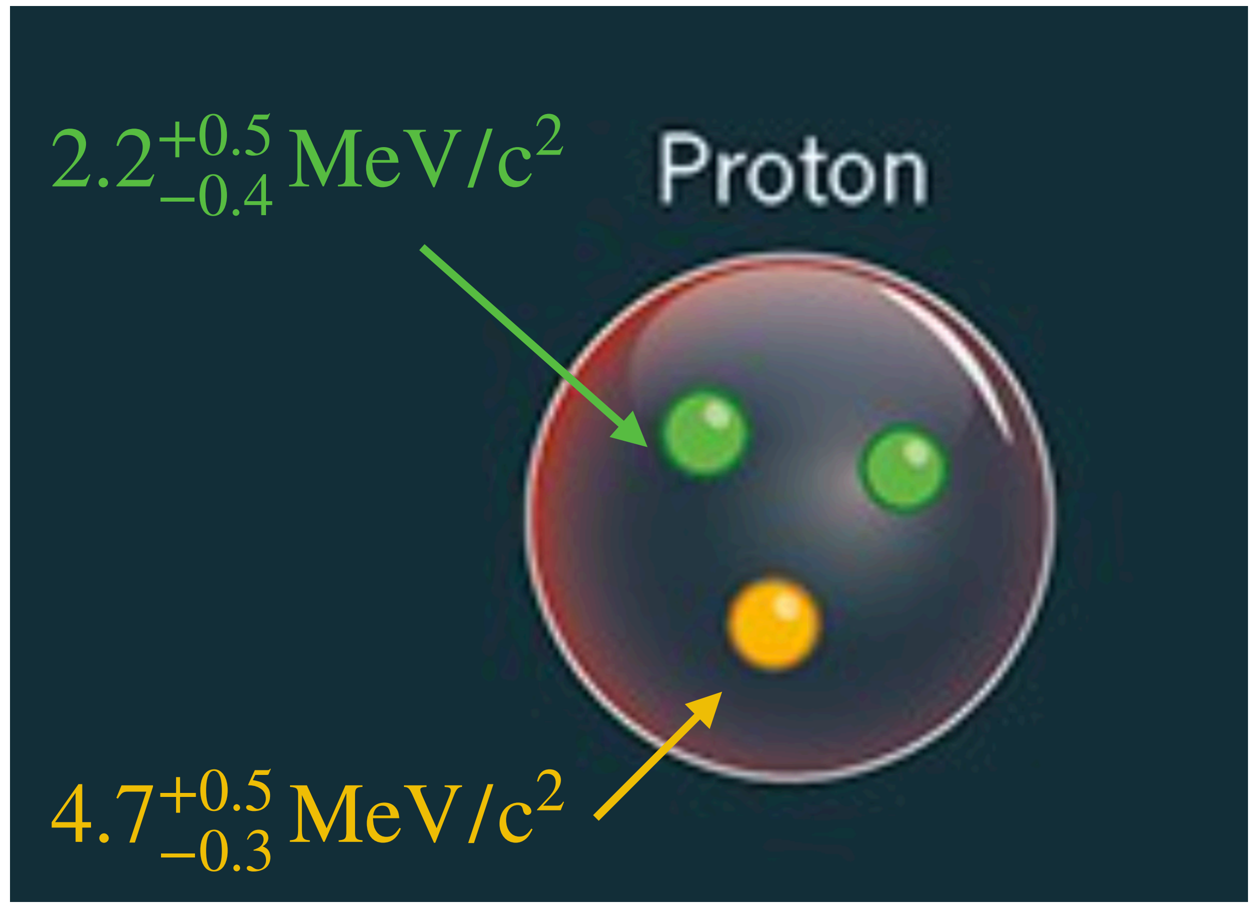
Tool for discovery

- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

The Higgs from the Nuclear Standpoint



939.56542052(54) MeV/c^2



938.27208816(29) MeV/c^2

The proton and the neutron are the same particle (same strong isospin double)…

The neutron is heavier than the proton with a mass difference of ~0.1%

95% of the mass of nucleons from quark condensates and confined quark and gluon kinetic energies.

1% from electromagnetic effects (slightly larger for proton)

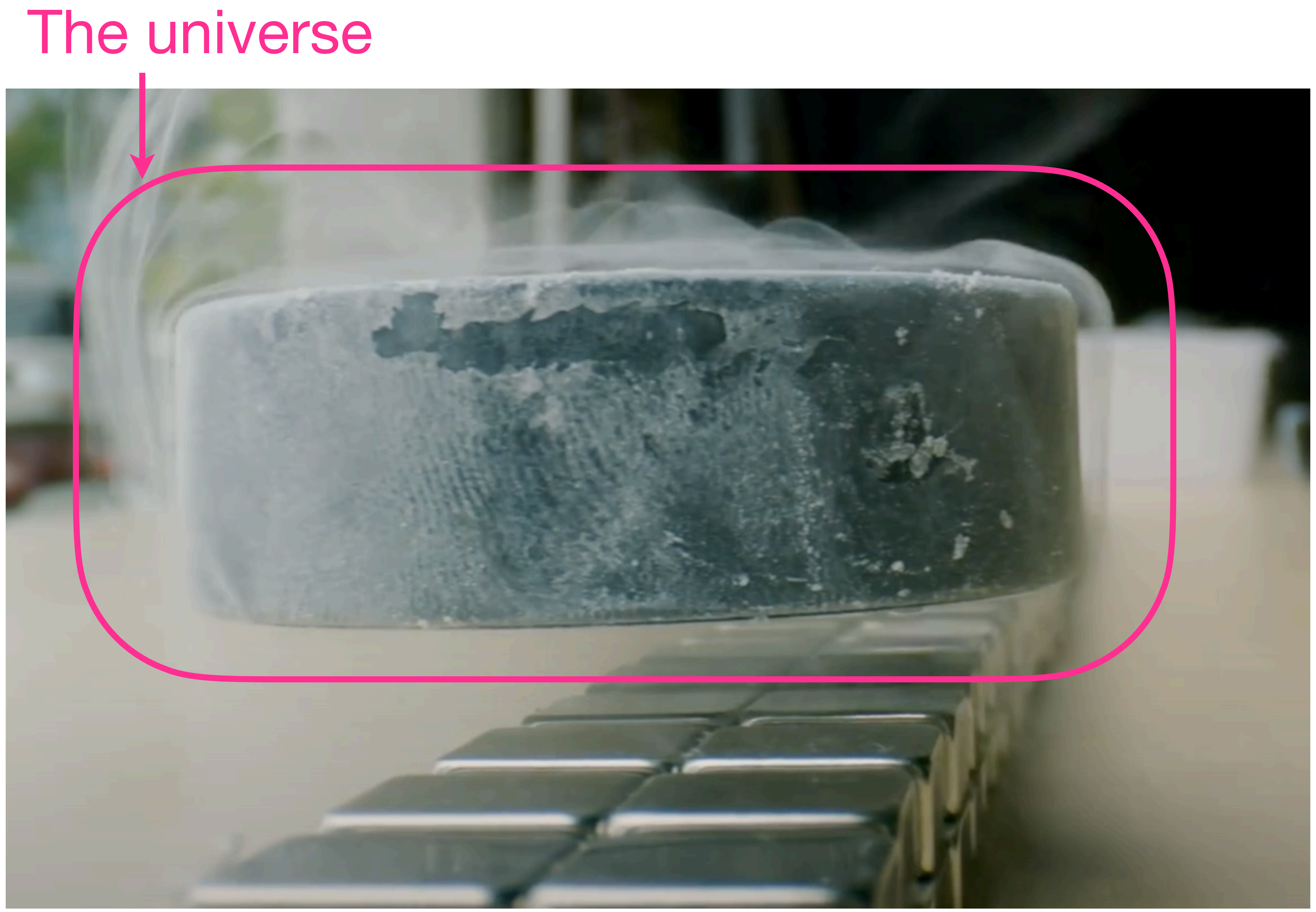
4% from its constituent quarks

With even just slightly different masses, nuclei as we know them would not be stable…

This tiny difference is due to the Higgs coupling to quarks!

Other important fundamental concepts borrowed from quark condensates and the strong interaction…

An Accurate Analogy



Superconductivity

SC (BCS) Theory	Higgs Mechanism
Cooper pair condensate	Higgs field (No dynamic explanation)
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of the W and Z bosons

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

1957 – Bardeen, Cooper and Schrieffer
Phys. Rev. 108 (1957) 1175

Further reading : L. Dixon, “From superconductors to supercolliders”
(http://www.slac.stanford.edu/pubs/beamline/26/1/26-1-dixon.pdf)

Is the Higgs boson composite?

The Standard Model of Particle Physics

This is the Lagrangian density which contains the information about the dynamics of the considered system.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

Beauty: simplicity of these expressions, and interactions governed by gauge symmetries only 3 (EW) and 2 (QCD) parameters!

The Higgs Mechanism… postulates the **Higgs field**!

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Ugliness: number of free parameters (26 altogether) not governed by symmetries

The strong CP problem

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu}$$

$$\theta < 10^{-10}$$

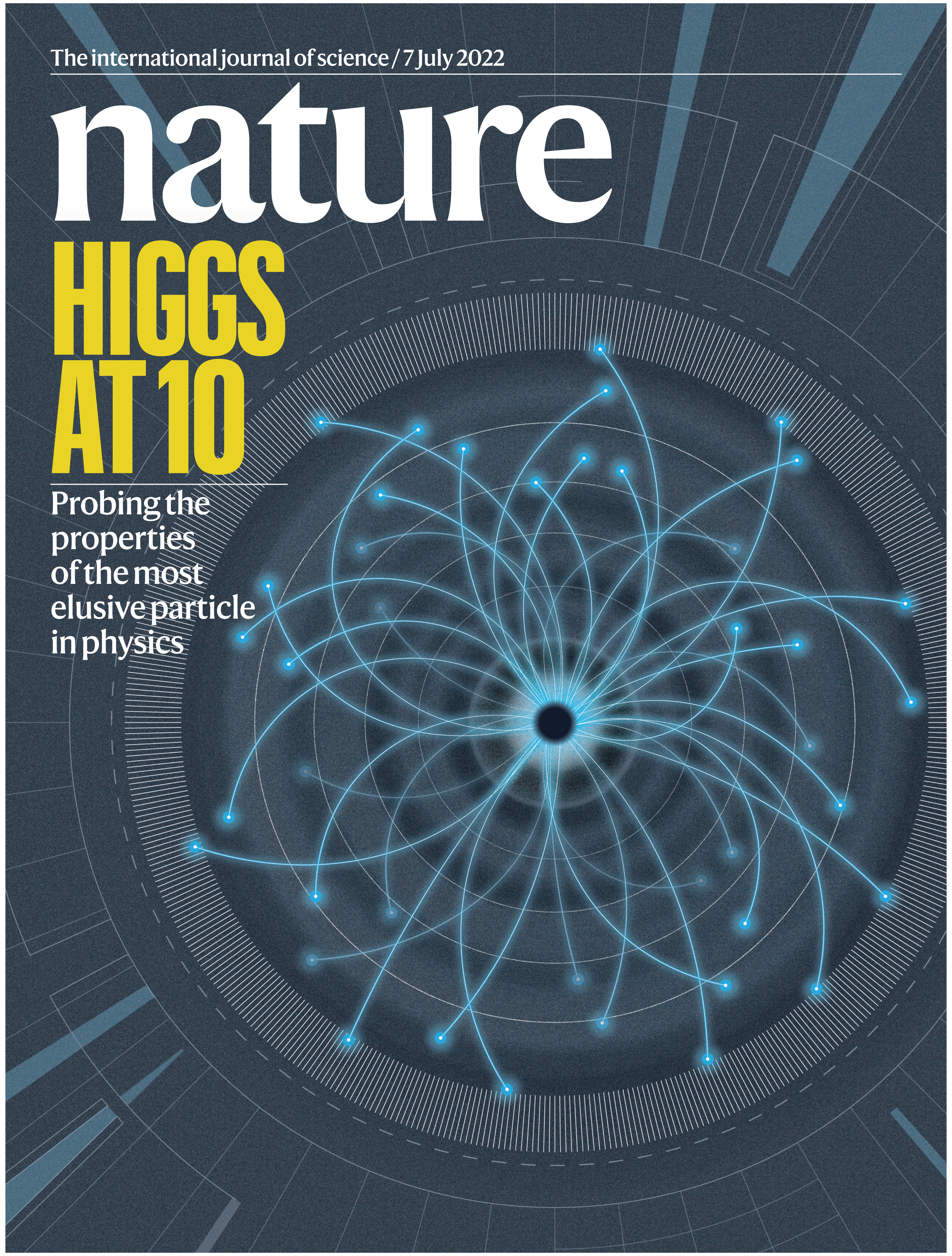
From neutron electric dipole moment measurements

Hierarchies

- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

Why are masses so different? Yukawa couplings are set by hand!

Already more than a Decade Ago!


The international journal of science / 7 July 2022

nature

HIGGS AT 10

Probing the properties of the most elusive particle in physics

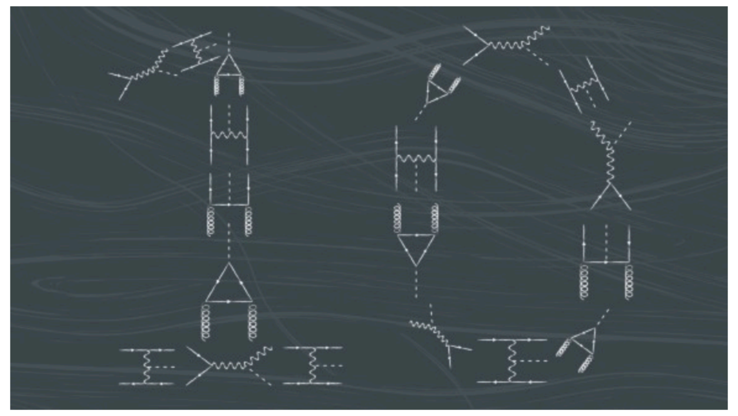
nature portfolio

nature > collection

Collection | **04 July 2022**

The Higgs boson discovery turns ten

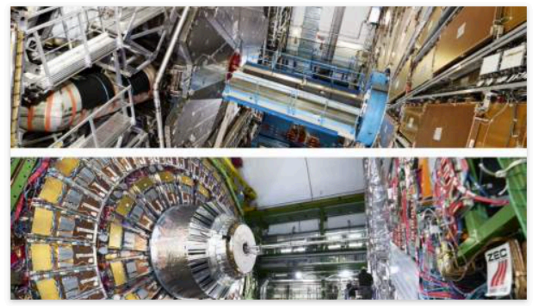
The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature*, *Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.



CERN 10 years HIGGS boson discovery

Higgs 10 symposium at CERN

CERN news



ATLAS and CMS release results of most comprehensive studies yet of Higgs boson's properties

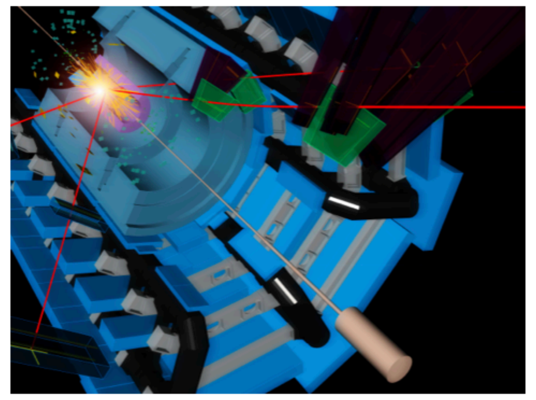
The collaborations have used the largest samples of proton–proton collision data recorded so far by the experiments to study the unique particle in unprecedented detail

News | Physics | 04 July, 2022

Higgs10: When spring 2012 turned to summer

It was just a few short weeks in mid-2012, but they were so intense that it felt like years. As 4 July drew near, the ATLAS and CMS experiments could sense that they were homing in on something big.

News | At CERN | 04 July, 2022



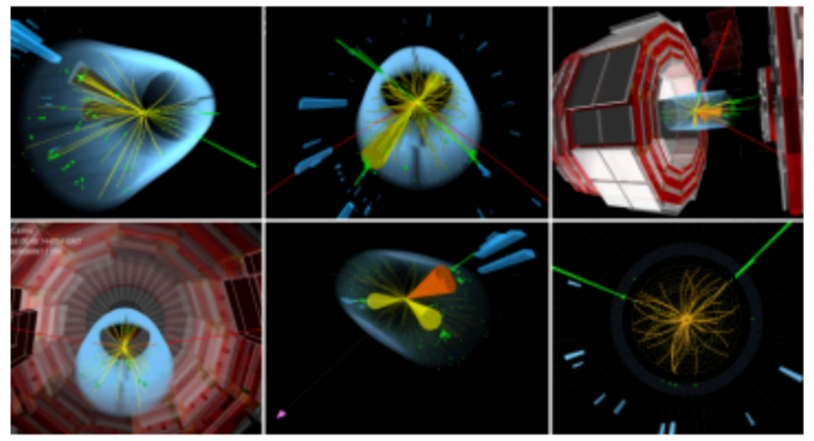
10 years of Higgs research

The ATLAS Collaboration at CERN has released its most comprehensive overview of the Higgs boson. The new paper, published in the journal Nature, comes exactly ten years after ATLAS announced the discovery of the Higgs boson. In celebration of this anniversary, a special all-day symposium on the Higgs boson is currently underway at CERN.

Press Statement | 4 July 2022

ATLAS news

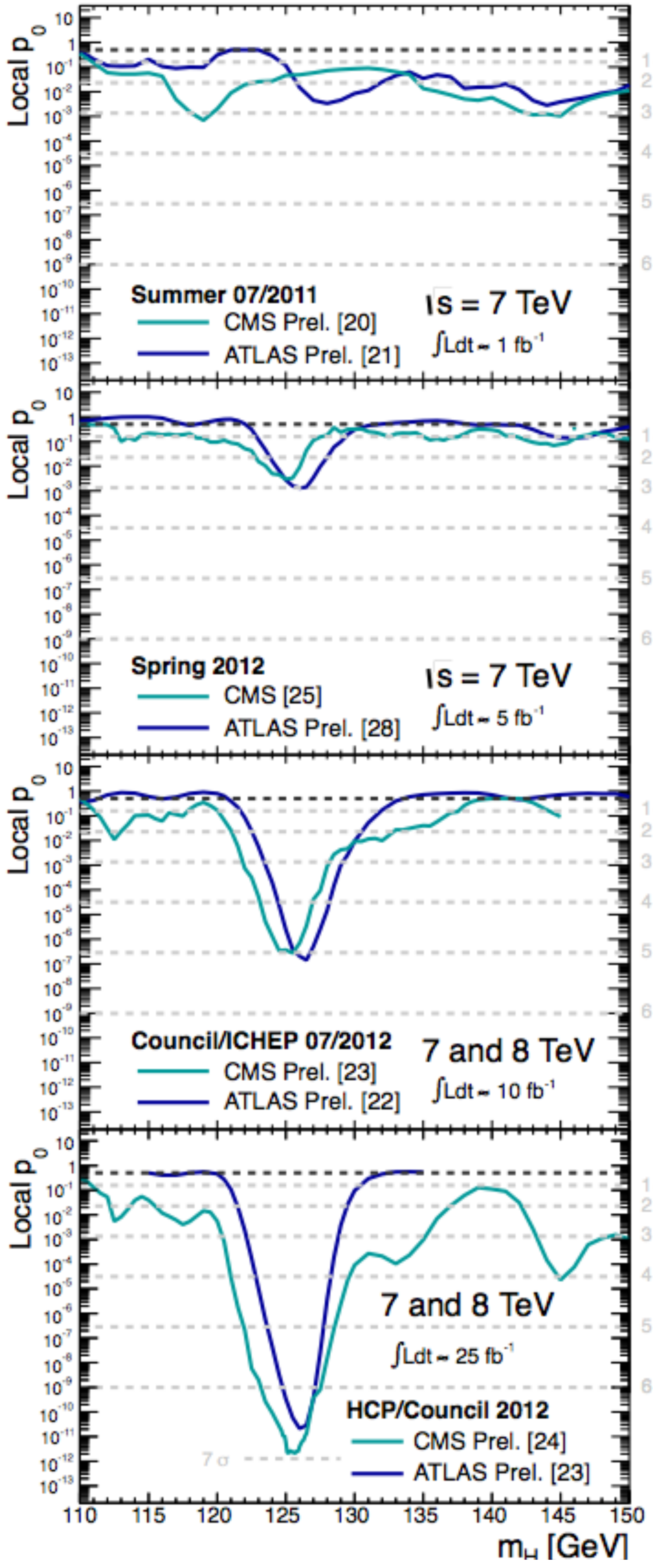
CMS news

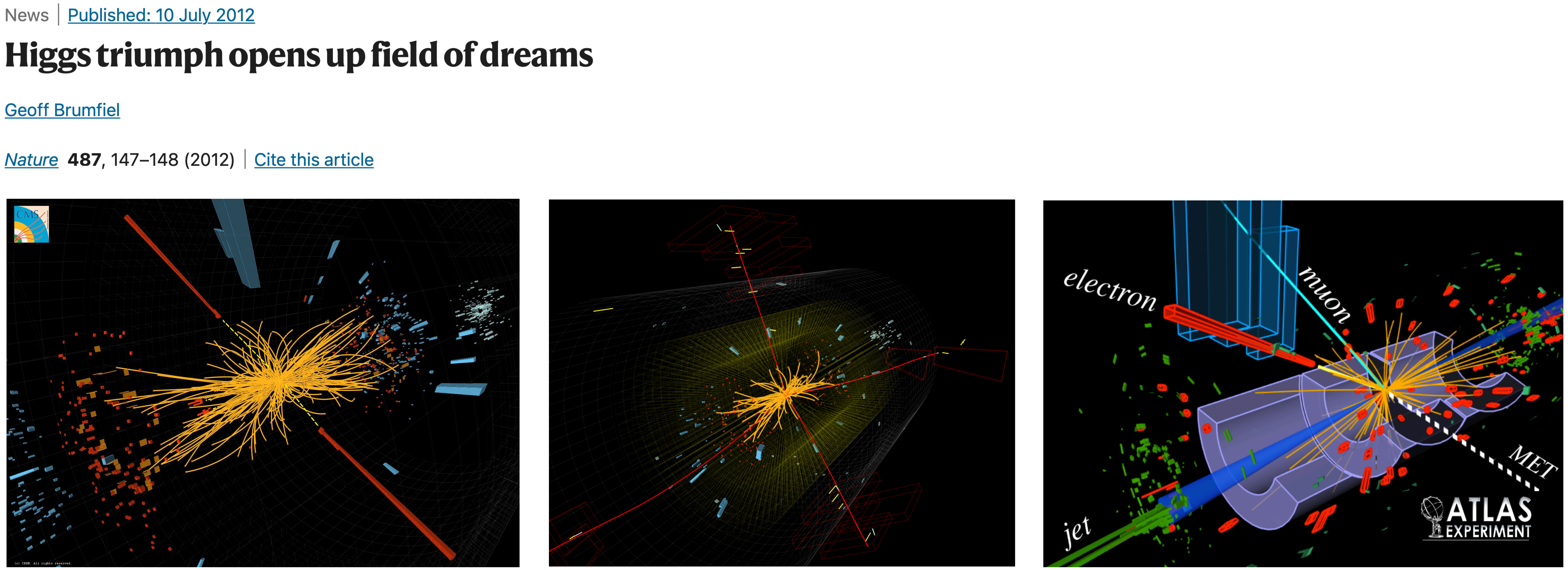


THE HIGGS BOSON TURNS 10: RESULTS FROM THE CMS EXPERIMENT

04 JUL 2022 | AJAFARI | PHYSICS

The Discovery of the Higgs Boson





News | Published: 10 July 2012

Higgs triumph opens up field of dreams

Geoff Brumfiel

Nature **487**, 147–148 (2012) | Cite this article

The discovery of the Higgs boson is a landmark result in particle physics

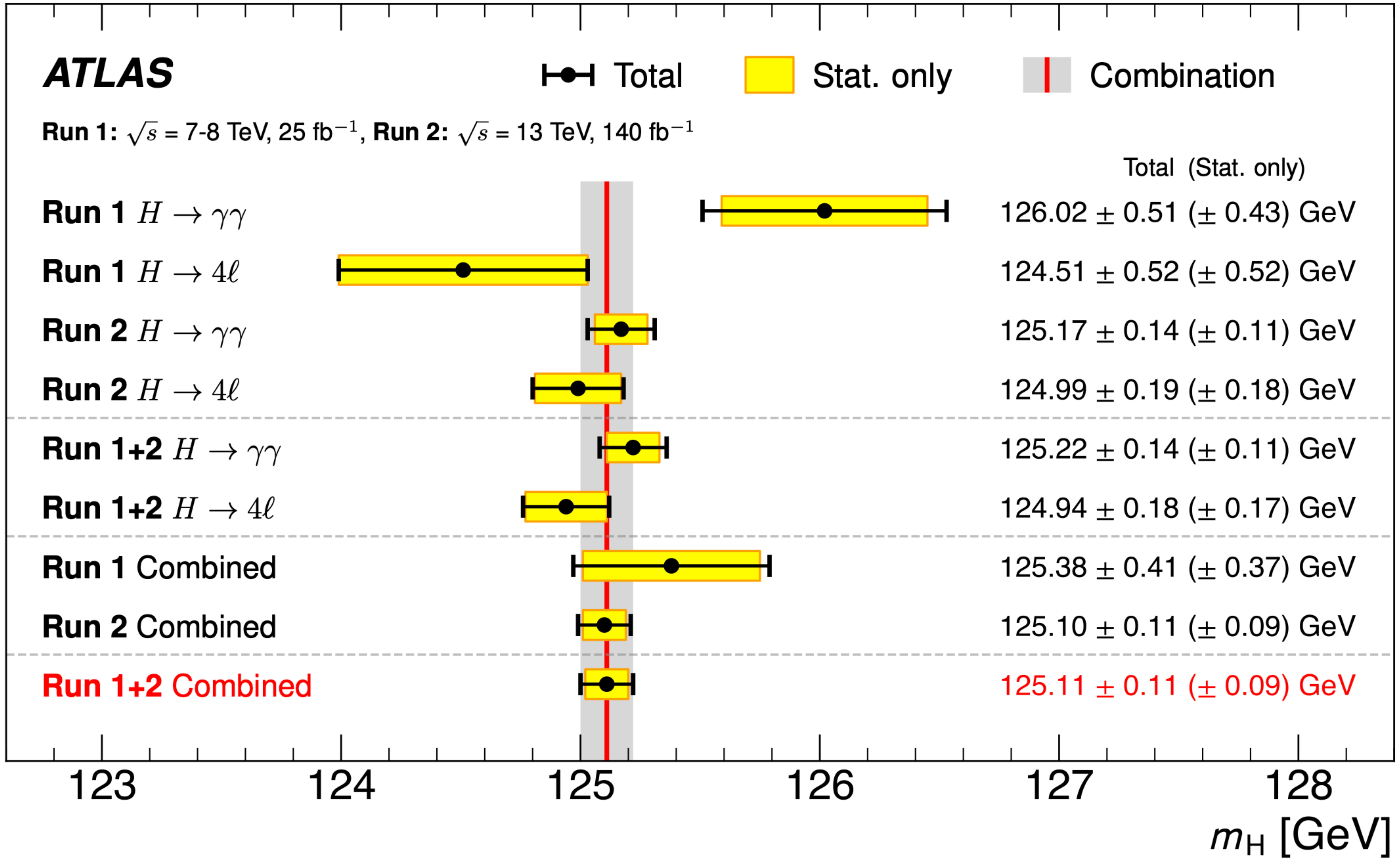
- A textbook discovery (achieved faster than anticipated)
- A gift of nature (a Higgs boson mass maximising the number of channels in which to measure its coupling properties)

At the time of the discovery the Higgs boson mass was already known to be 125 GeV at 0.5% precision.

First Precision Measurement at the LHC!

Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.
- Systematics dominated by experimental uncertainties.
- Reached at Run 1 a precision of 0.2%.
- Precision reached **0.09%** (below permil!)



Precision foreseen at HL-LHC 10-20 MeV

Similar precision by CMS

What have we Learned from Knowing its Mass?

Vacuum (meta) stability

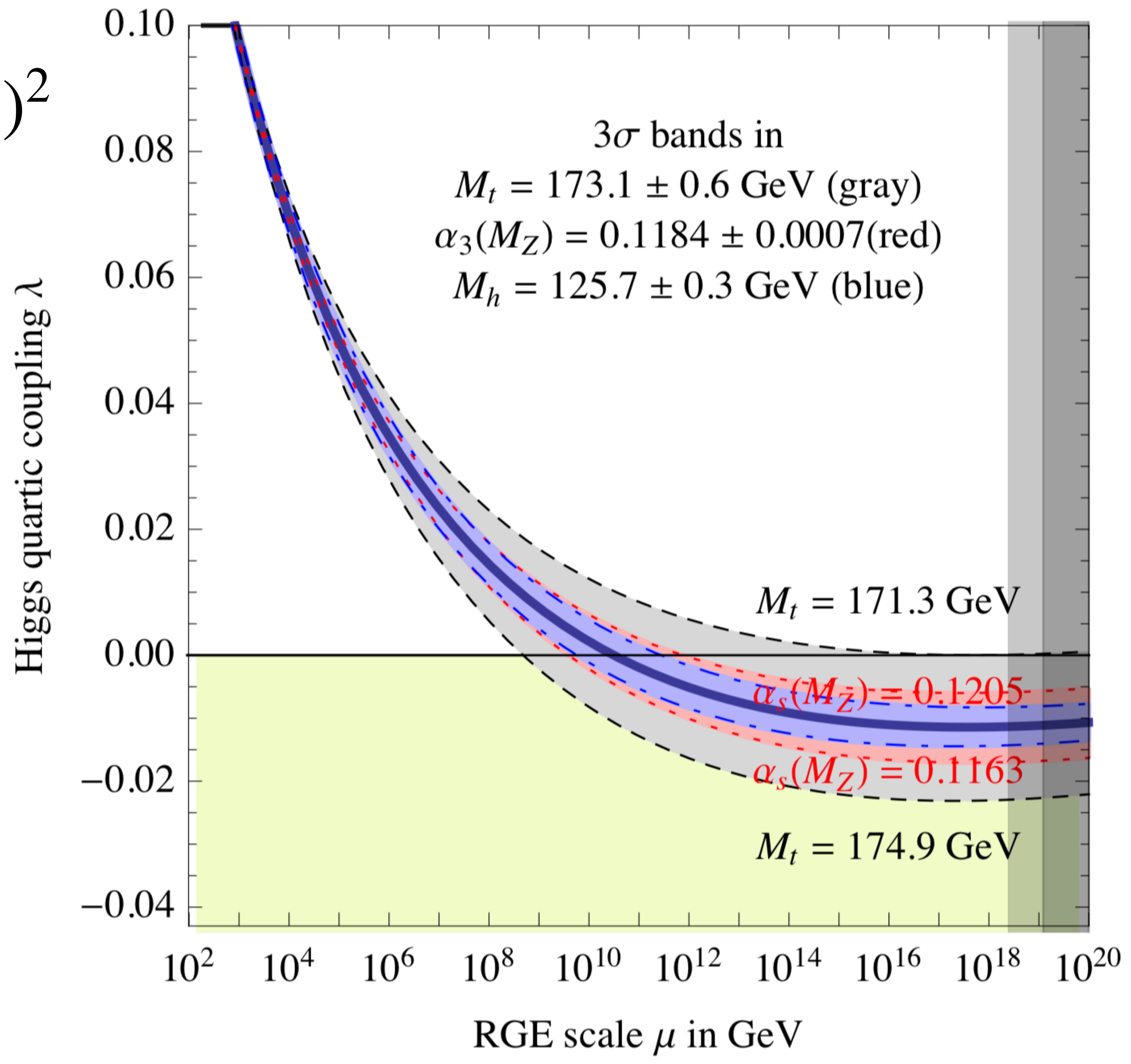
Running of the Higgs self coupling, **assuming SM** only at high scale

$$V(\phi) = -m^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2$$

$$m_H = \sqrt{2\lambda}v$$

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

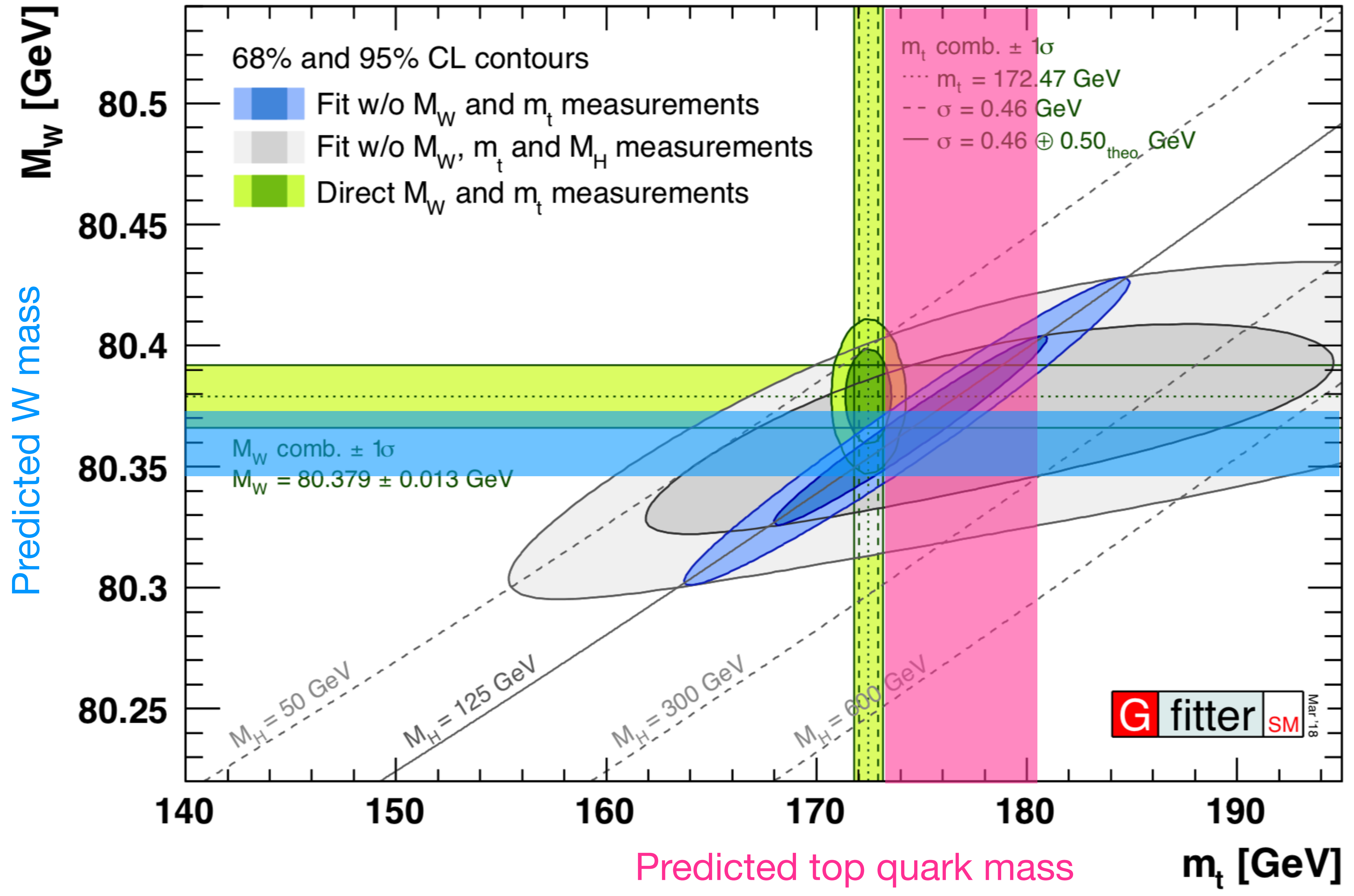
Nima Arkani Hamed



Near vanishing coupling at the Planck scale

The role of Precision

Electroweak Measurements consistent at quantum corrections level (also assumes SM)

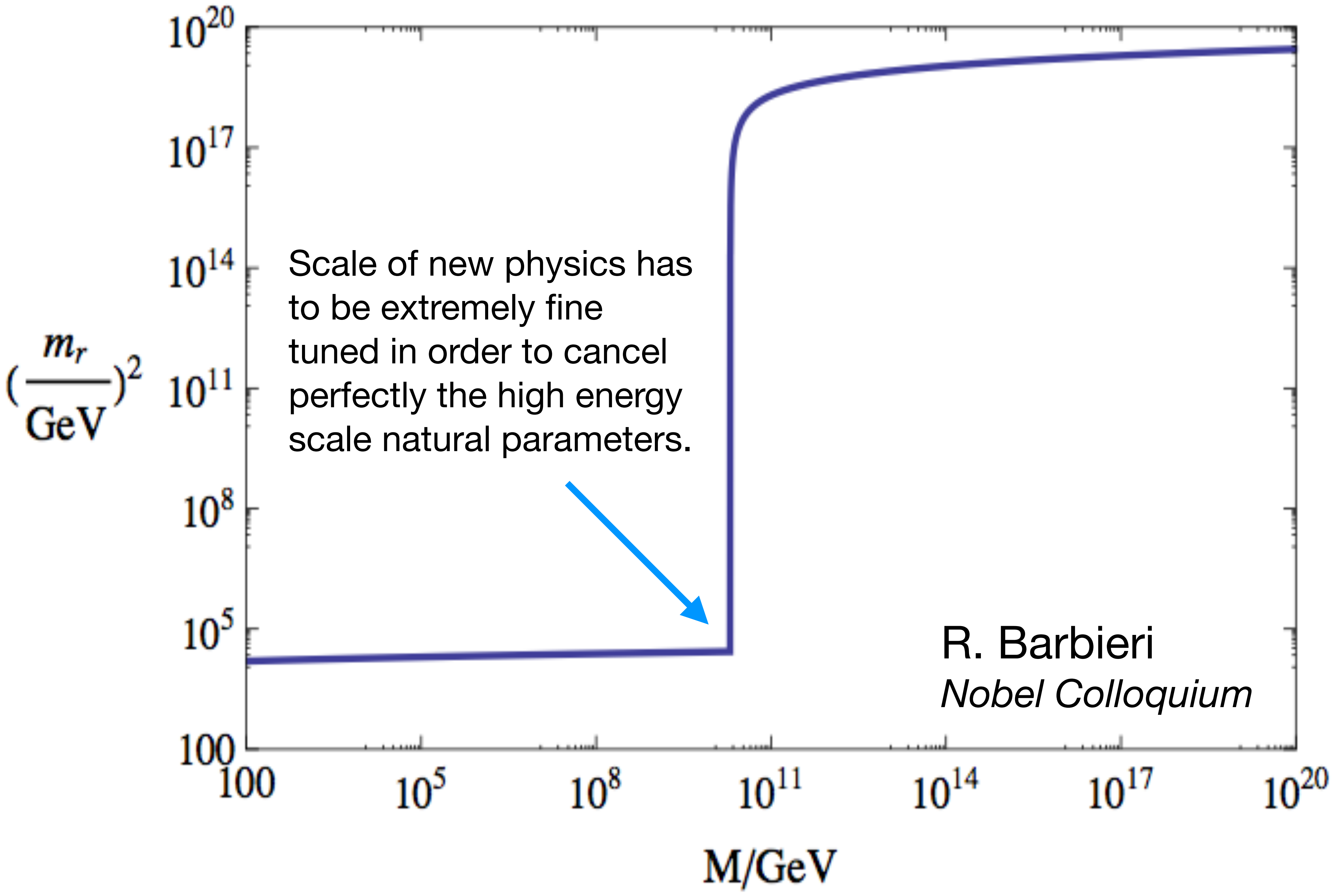


Precision measurements allow to make predictions!!

Assuming the SM, the top quark mass and Higgs boson mass were (approximately) known before being discovered!

The (running) Higgs mass and the Naturalness Problem

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent, not an issue per se (renormalisation) but if there is new physics at a high scale a **threshold in the running Higgs mass** will appear **implying a fine tuning of the mass at the high scale!**



Scale of new physics has to be extremely fine tuned in order to cancel perfectly the high energy scale natural parameters.

R. Barbieri
Nobel Colloquium

Solutions explored:

- **Weakly coupled** (SUSY)
- **Strongly coupled** (Composite)
- **Warped extra dimensions**

To be natural, solutions involve new physics at close-by energy scales! Or invoke the **Anthropic principle**…

The Higgs Field

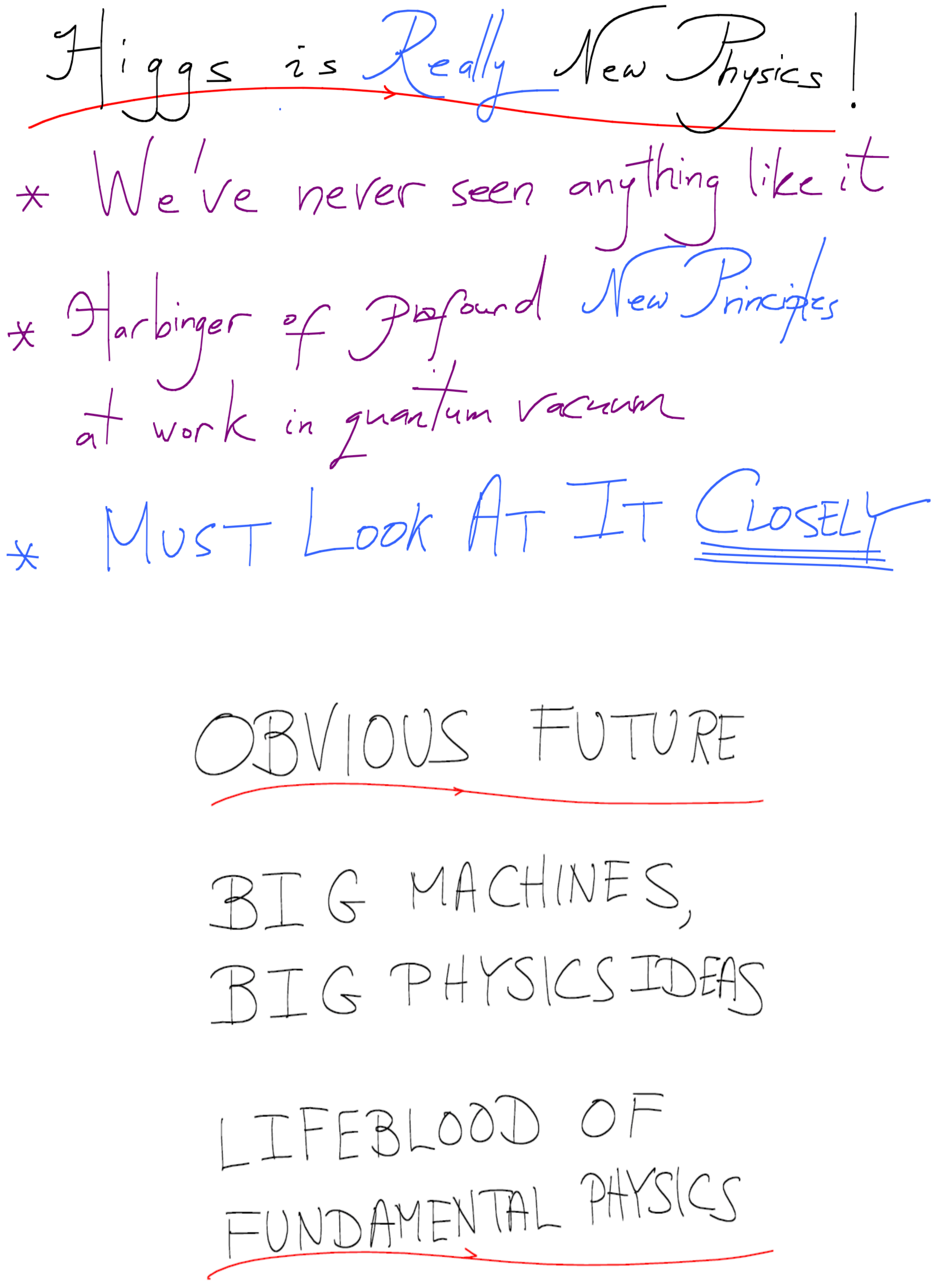
The Higgs particle is related to most of the fundamental questions we have about nature

The Higgs particle completes the Standard Model (SM) a theory that now explains all our observations at colliders.

However the SM is very far from explaining everything!

- The (origin of) Higgs mass is one of the greatest mysteries of fundamental physics! The Naturalness problem
- The nature of Dark Matter , is the Higgs responsible for its mass?
- The nature of Dark Energy The cosmological constant problem
- The origin of the asymmetry between matter and anti-matter in the universe? CP Violation and EW Phase transition
- The nature of neutrinos, their masses and the widely different masses between fermions. Flavour Hierarchy problem
- Why do electrons have precisely the same charge as the protons? Grand Unification
- Why is the electric dipole moment of the neutron so small? Answers involve a scalar field the axion The Strong CP problem
- What fuels inflation - involves the existence of a fundamental scalar, the **inflaton**?
- Gravity at small distance scales - attempted descriptions also often imply a fundamental scalar field the **Dilaton**

Opportunities at Future Colliders at the Energy Frontier



Higgs is Really New Physics!

- We've never seen anything like it
- Harbinger of Profound New Principles at work in quantum vacuum
- MUST LOOK AT IT CLOSELY

OBVIOUS FUTURE

BIG MACHINES,
BIG PHYSICS IDEAS

LIFEBLOOD OF
FUNDAMENTAL PHYSICS

N. Arkani Hamed

Energy Frontier Vision in which the Higgs boson plays a very important role

- **Short term**: immediate priority is the success of the HL-LHC (construction, operations, computing and software, and physics program)

- **Medium term**: e+e- Higgs factory, either based on a linear (ILC, C3, CLIC) or circular collider (FCC-ee, CepC) to enable an unprecedented precision investigation of the EW sector.

- **Long term**: a 100-TeV or more proton-proton collider (FCC-hh, SppC) or a 10-TeV muon collider to directly probe the order 10 TeV energy scale

A Scientific Mission for the 21st Century

LHC Run 2
2014-2018 13 TeV
100% to 2x Nom. Lumi, PU 40
Int. Lumi.190 fb-1

Higgs couplings to Fermions of the third generation (top, bottom and taus)!

LS2
2018-2022
Experiments Phase-I and accelerator upgrades

HL-LHC (Runs 4-6)
2029-2041 13.6 - 14 TeV and 2x Nominal Luminosity, PU 140 - 200
Int. Lumi. 3000 fb-1

di-Higgs boson production and Higgs self coupling and precision Higgs physics!

CLIC 380 GeV- 3 TeV

ILC 250 GeV - 1 TeV

Cool Copper Collider 250 - 550 GeV

LS1
2012-204
Consolidation of LHC interconnections

LS3
2026-2029 HL-LHC installation and major exp. upgrades

FCC-ee 90 - 265 GeV

FCC-hh 100 TeV

CepC 90 - 240 GeV

SppC

LHC Run 1
2009-2012 7-8 TeV
75% Nom. Lumi, PU 30-40
Int. Lumi. 30 fb-1

Discovery of the Higgs Boson, measurements of Higgs Boson couplings to bosons (gluons, photons, W and Z)

LHC Run 3
2022-2026 13.6 TeV
2x Nom. Lumi., PU 60
Int. Lumi. 450 fb-1

Higgs couplings to Fermions of the second generation (muons) and more rare decays

Muon Collider

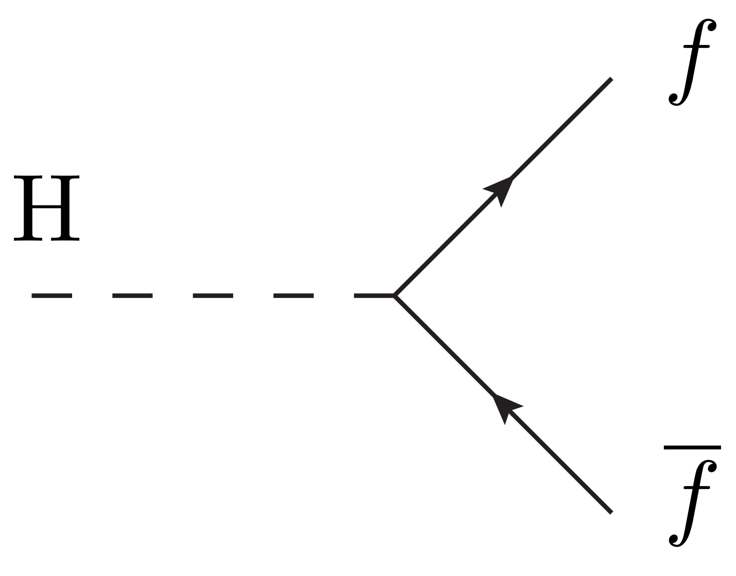
LHC

Ultimate Precision e^+e^-

Ultimate Energy (pp, $\mu^+\mu^-$)

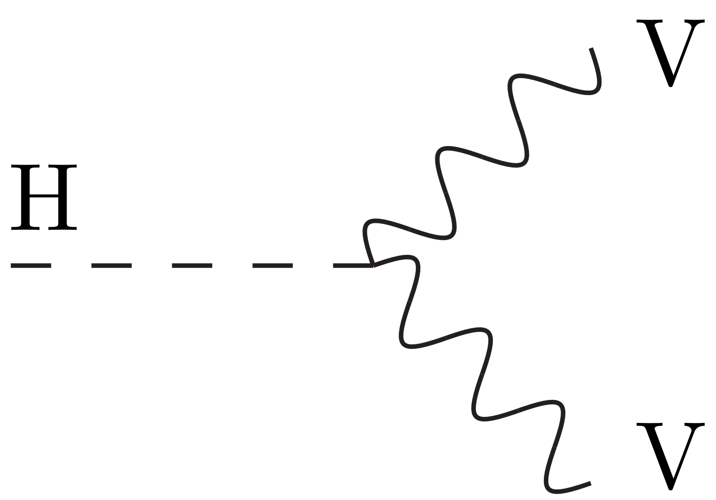
Three Pillars of Higgs Physics at Colliders

All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson! A very predictive model!



$$\frac{m_f}{v}$$

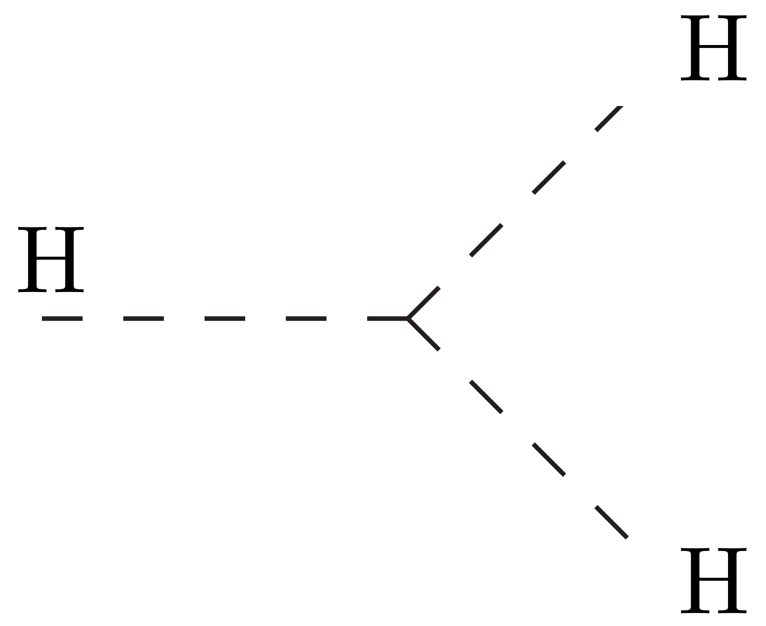
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



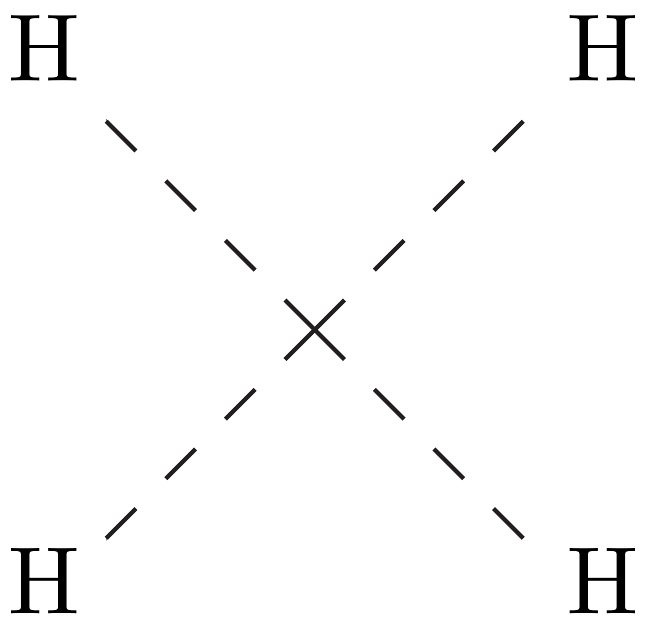
$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

This term could not exist without a vev



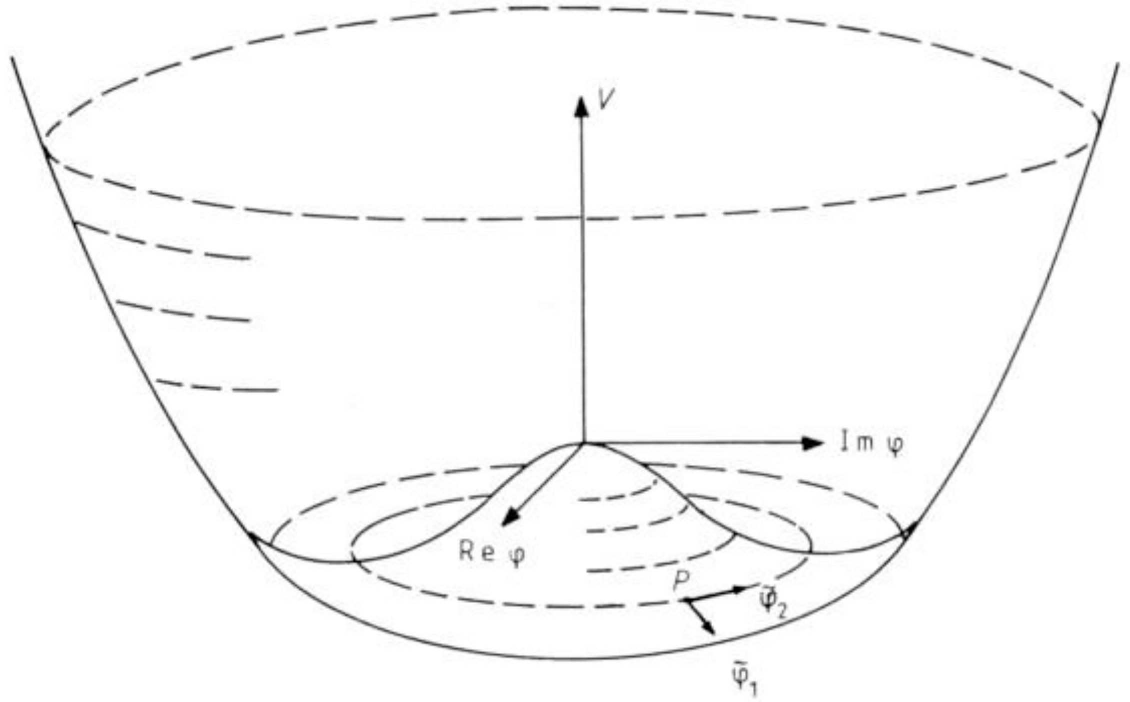
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$\boxed{V(\phi)}$$

Spontaneous Symmetry Breaking



$$V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

In the SM EW transition is a cross over does not fulfil requirements for baryogengesis, studying the Higgs potential is an outstanding goal of the Higgs physics program

The Large Hadron Collider (LHC) - the Energy Frontier

Unrivalled at the Energy Frontier

13.6 TeV (centre-of-mass energy)

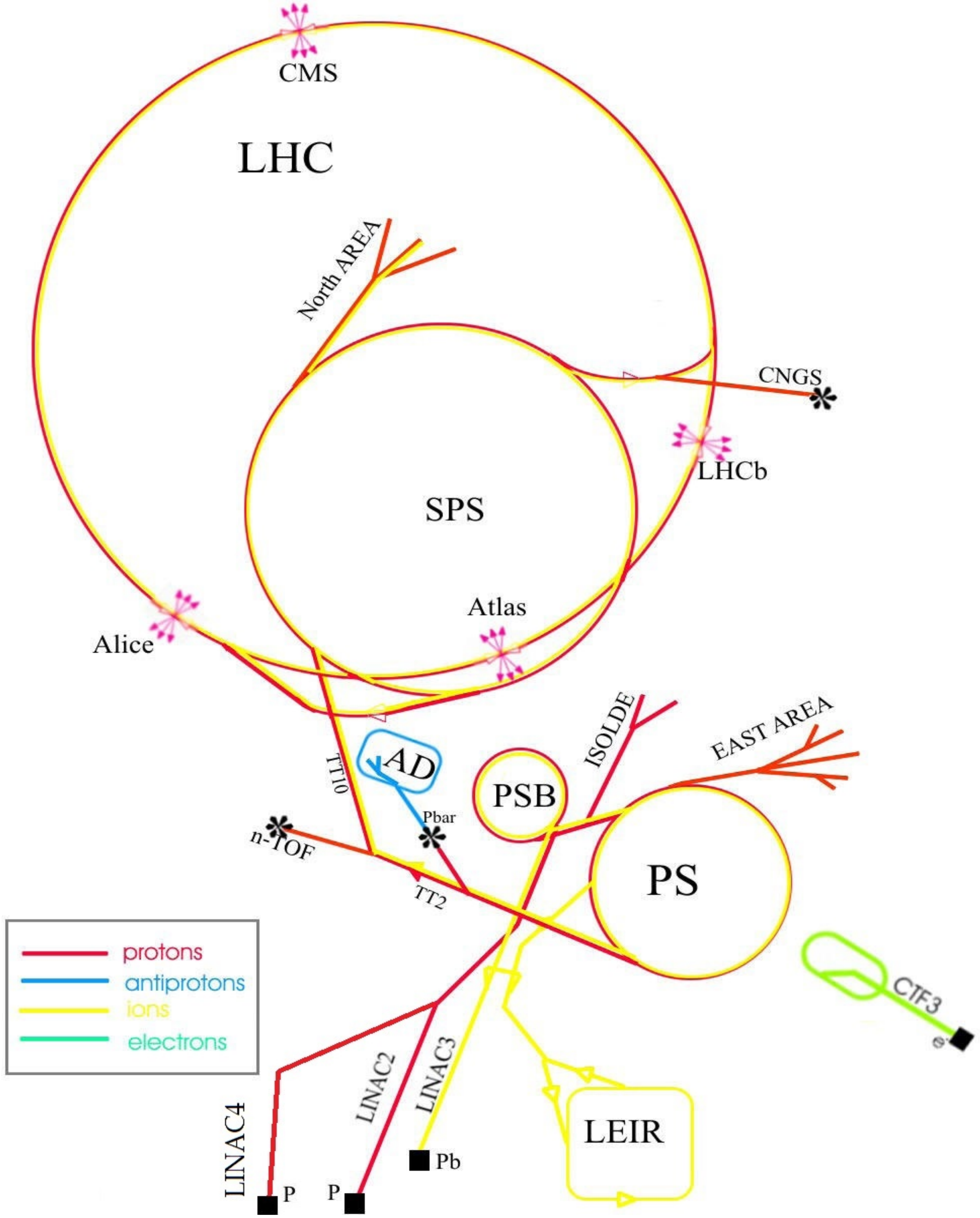
Outstanding at Intensity Frontier

Record Luminosity* of $2.26 \times 10^{34}\ cm^2 s^{-1}$

*Close to SuperKEKB at $2.22 \times 10^{34}\ cm^2 s^{-1}$

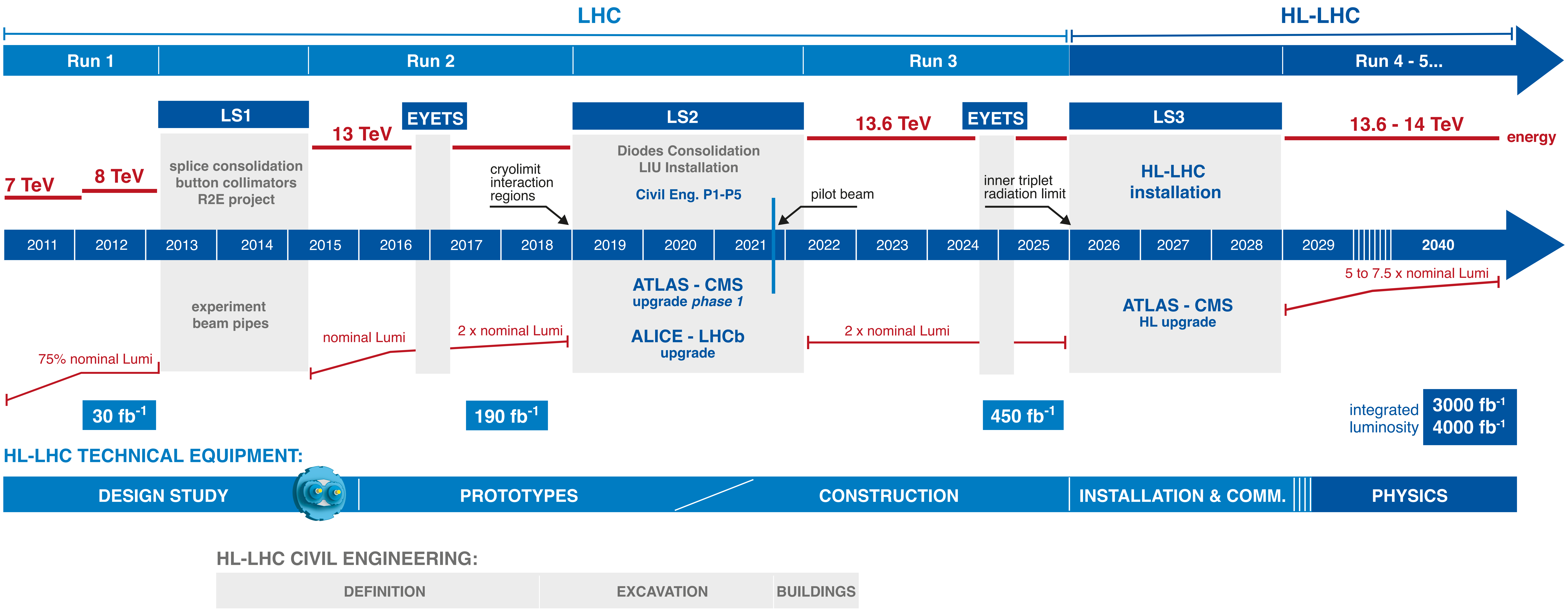
HL-LHC is a **Higgs factory** ~160 M Higgs events

In comparison Future ee up to ~1-4 M Higgs Events,
but much cleaner and « usable » events



The Large Hadron Collider (LHC) - the Energy Frontier

LHC / HL-LHC Plan



LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

7 TeV

8 TeV

LS1

splice consolidation
button collimators
R2E project

13 TeV

EYETS

cryolimit
interaction
regions

LS2

Diodes Consolidation
LIU Installation

Civil Eng. P1-P5

pilot beam

13.6 TeV

EYETS

inner triplet
radiation limit

LS3

HL-LHC
installation

13.6 - 14 TeV

energy

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2040

experiment
beam pipes

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

2 x nominal Lumi

ATLAS - CMS
HL upgrade

5 to 7.5 x nominal Lumi

30 fb^{-1}

190 fb^{-1}

450 fb^{-1}

integrated
luminosity

3000 fb^{-1}
4000 fb^{-1}

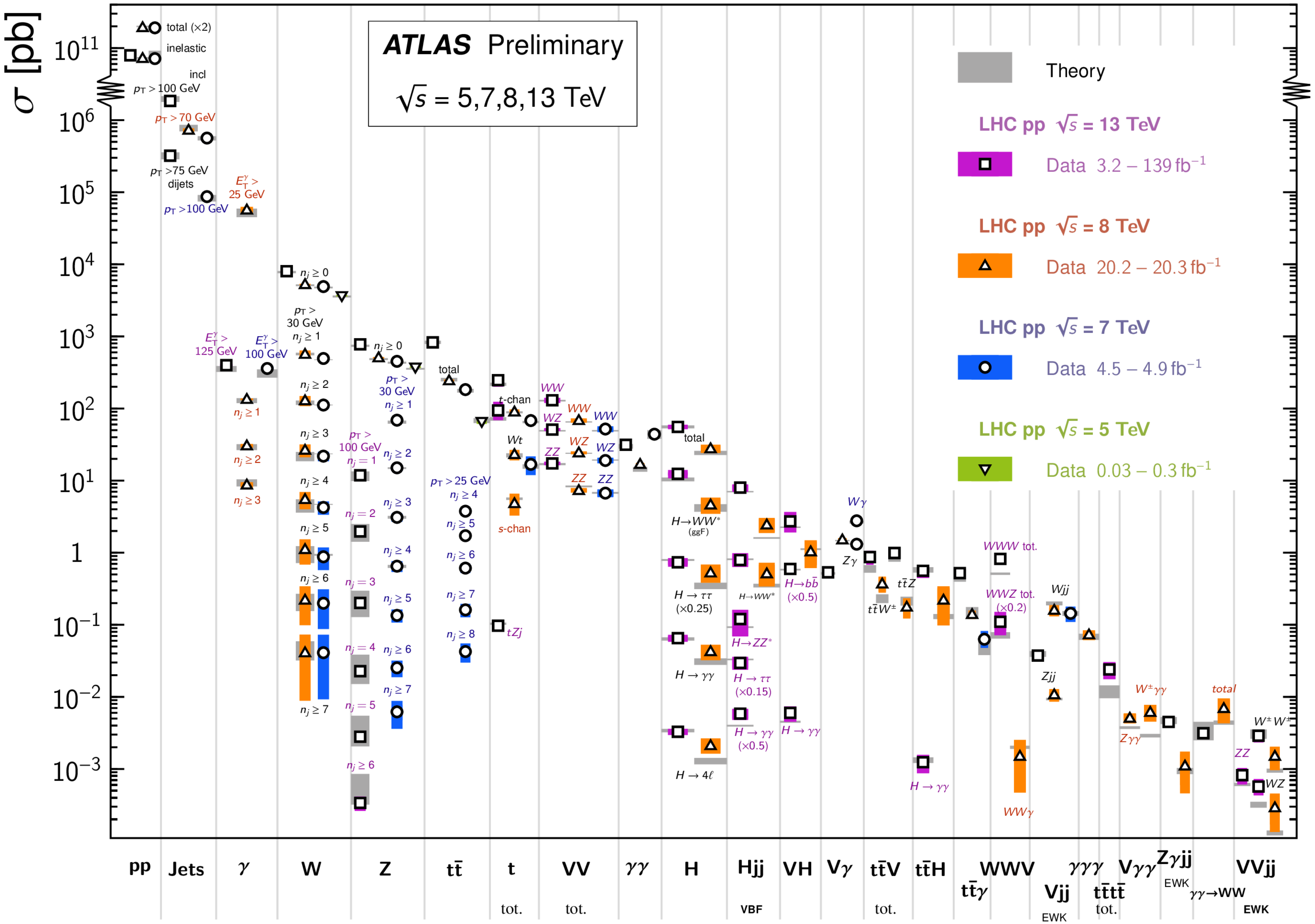
HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS

HL-LHC CIVIL ENGINEERING:

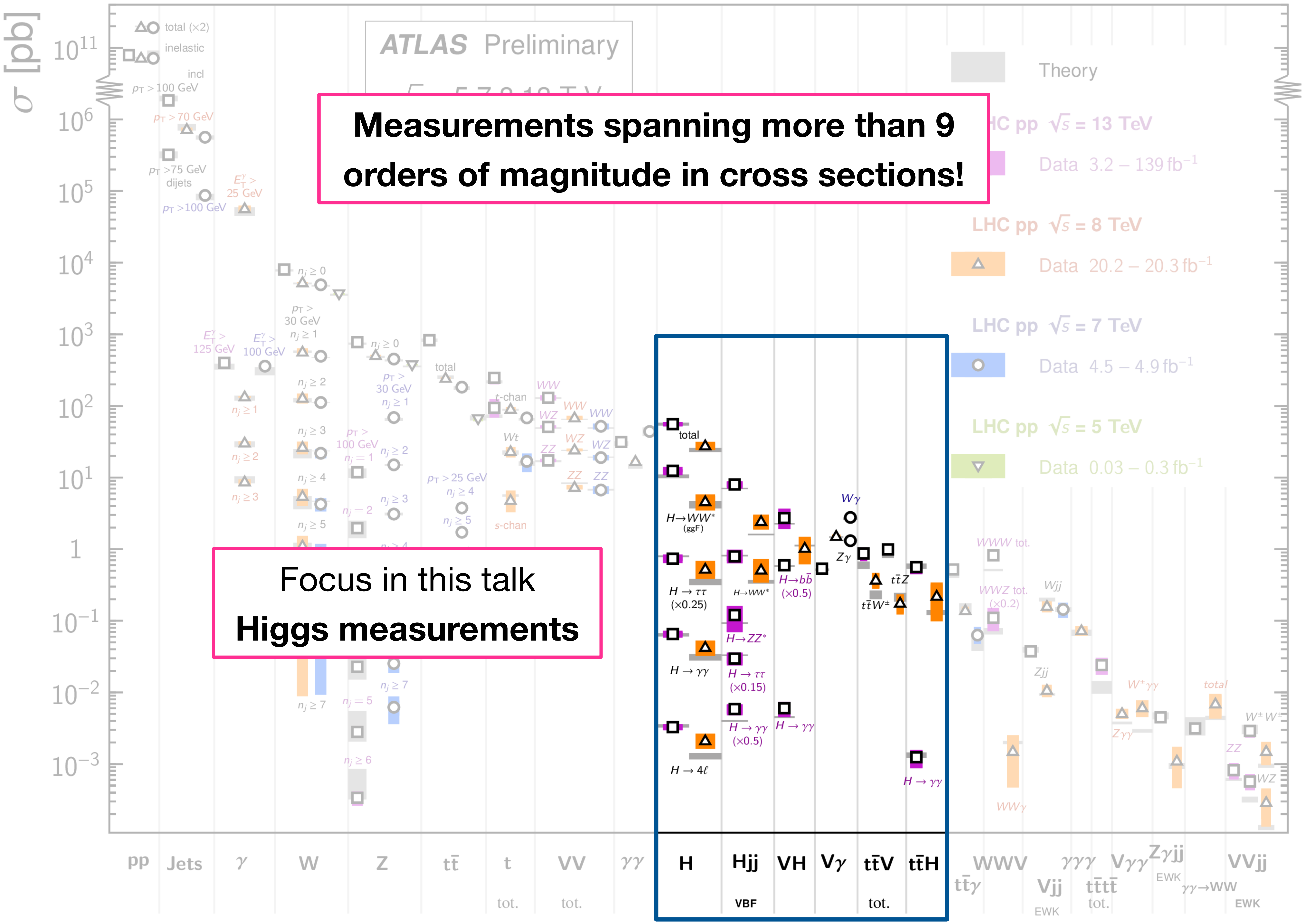
DEFINITION | EXCAVATION | BUILDINGS

Very broad overview!



- pp elastic scattering (down to the CNI regime), exclusive production, diffractive scattering
- Inclusive inelastic cross sections measurements
- QCD Jets, multi jets, photons and photons-jets
- DY (W,Z) and with (HF) jets, photons and Z Off mass shell, multi parton interactions
- Top pair production with (HF) jets or photons
- Diboson inclusive and VBS
- Single top Wt, t-channel and s-channel
- Tri-bosons
- Higgs production ggF-jets, VBF, HV, ttH
- Four tops, EWK dibosons…

Very broad overview!



Measurements spanning more than 9 orders of magnitude in cross sections!

Focus in this talk

Higgs measurements

- pp elastic scattering (down to the CNI regime), exclusive production, diffractive scattering
- Inclusive inelastic cross sections measurements
- QCD Jets, multi jets, photons and photons-jets
- DY (W,Z) and with (HF) jets, photons and Z Off mass shell, multi parton interactions
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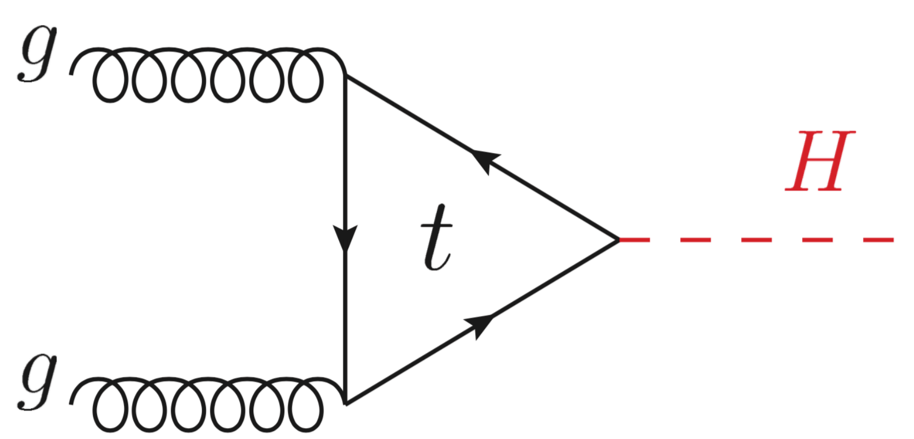
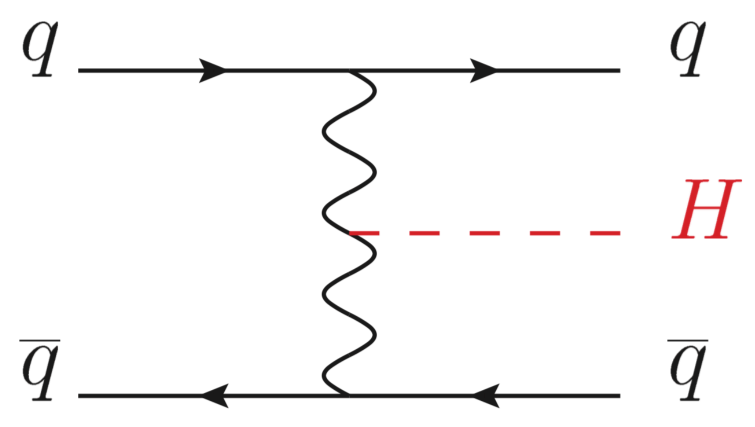
Signatures of the Higgs Boson

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

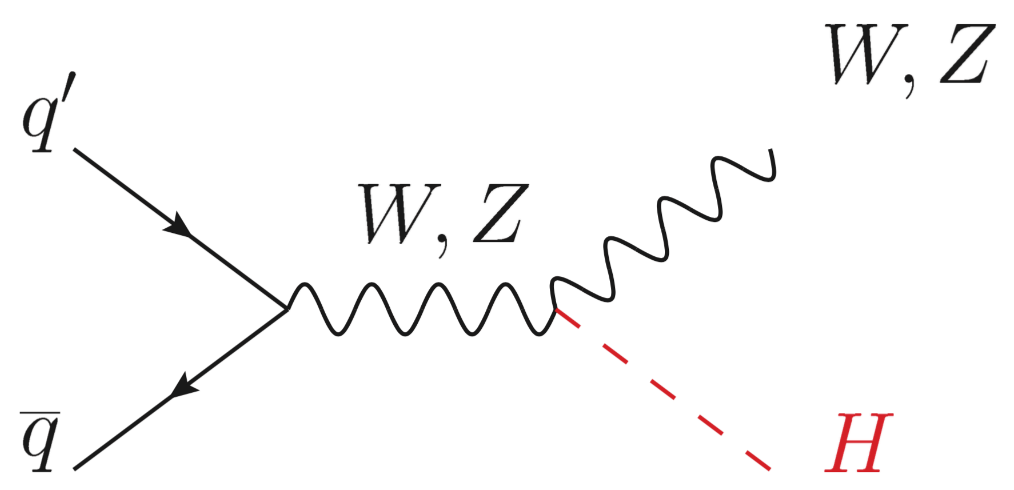
~8 M events produced



Vector Boson Fusion

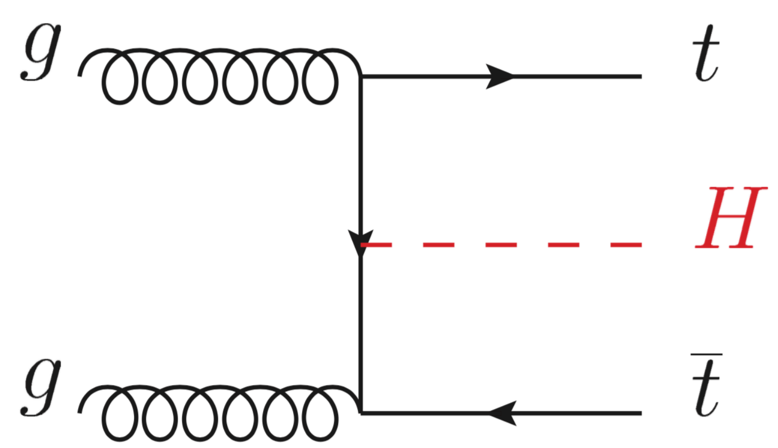
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

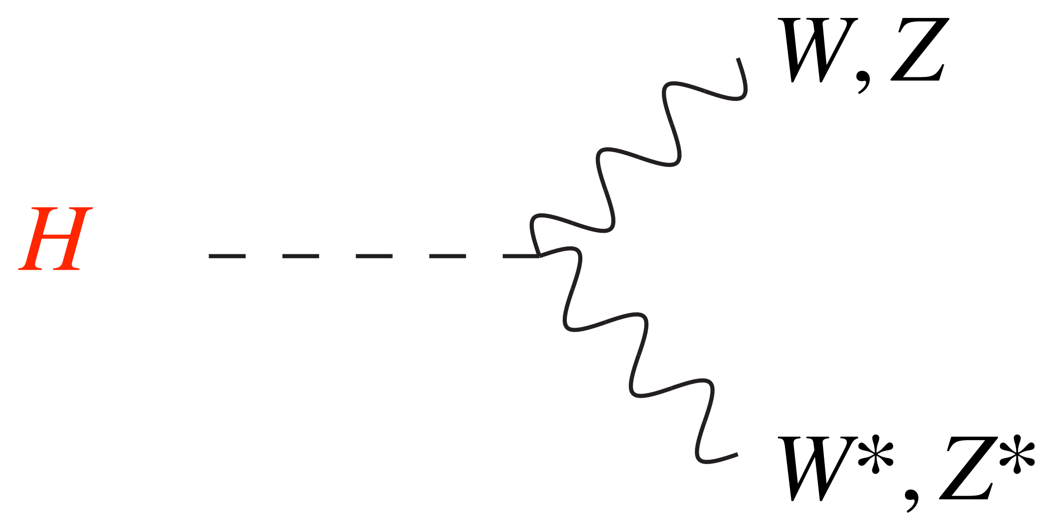
~400 k events produced



Top Assoc. Prod.

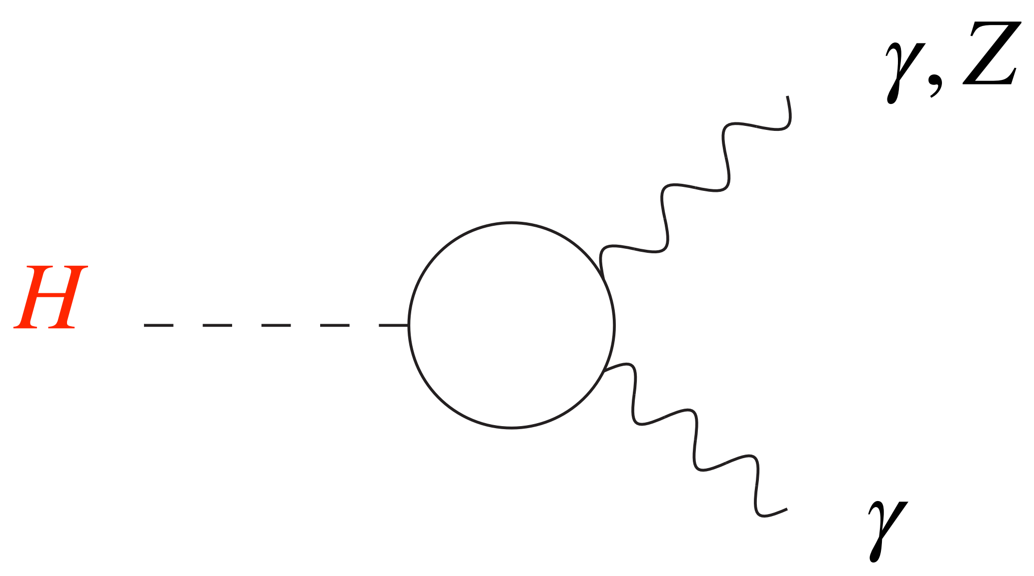
~80 k evts produced

Decay branching fractions



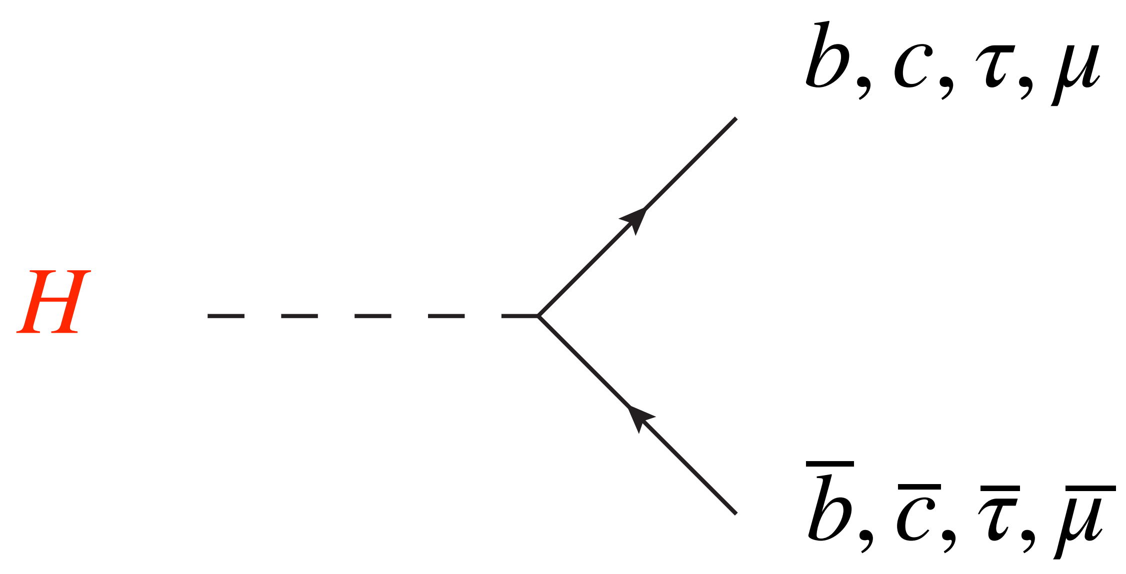
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

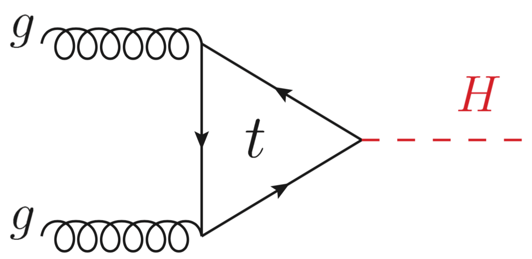
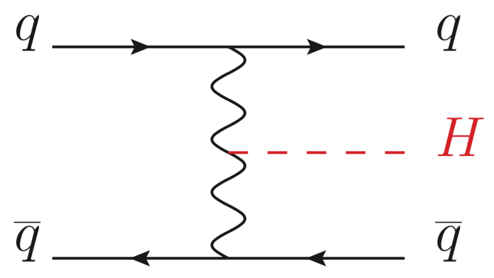
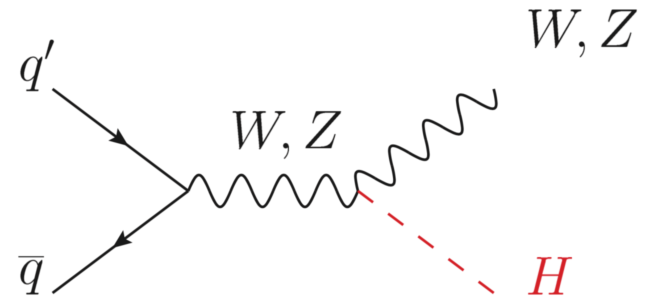
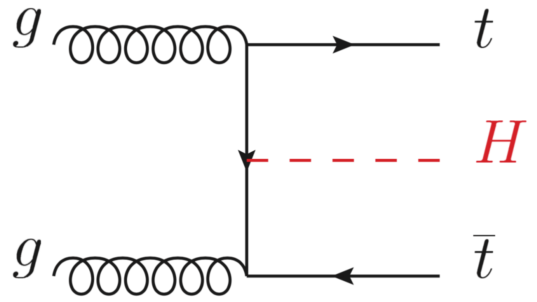
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

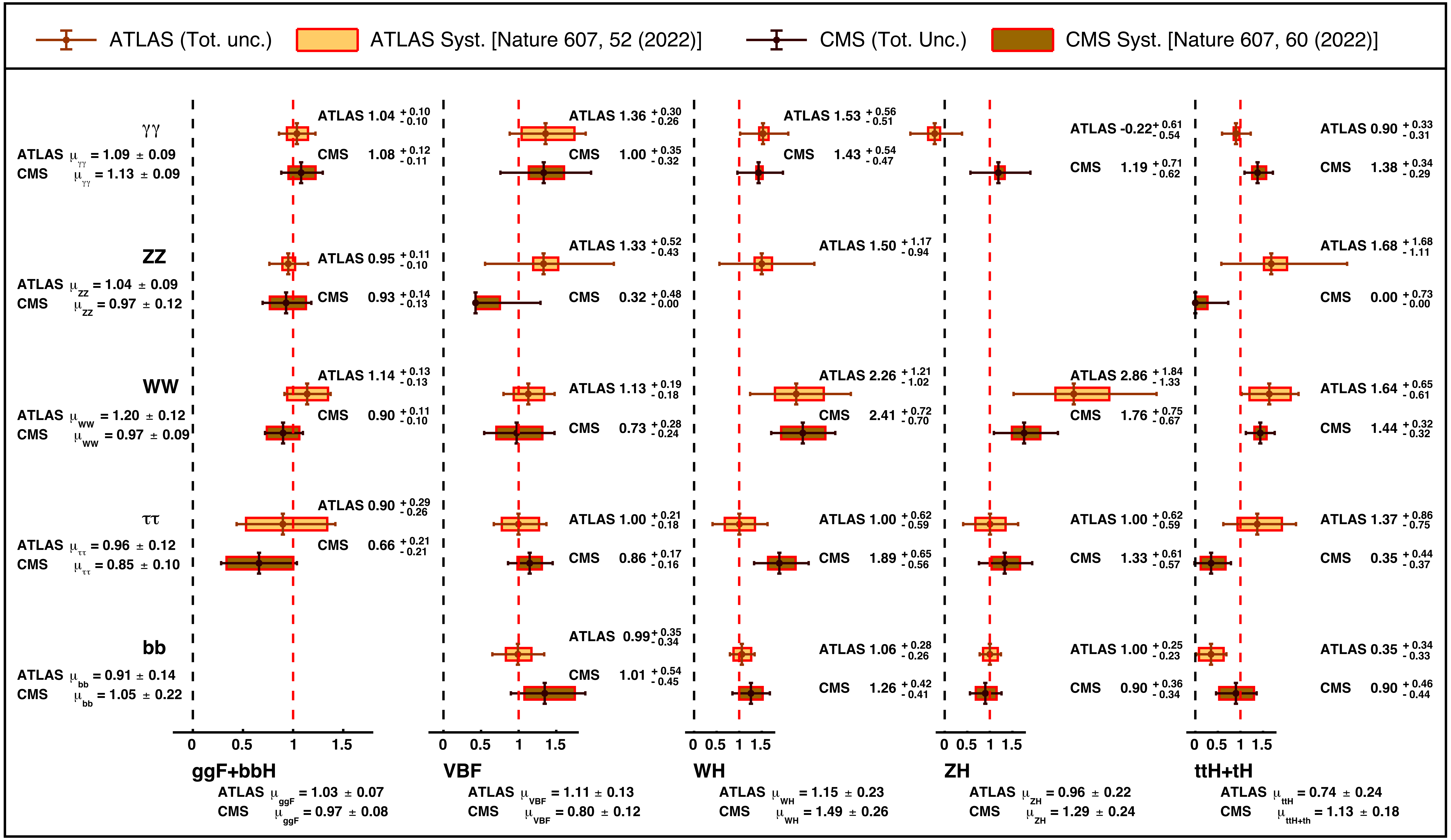
Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!

	Channel categories	Br	ggF  ~8 M vets produced	VBF  ~600 k vets produced	VH  ~400 k vets produced	ttH  ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

Very broad overview!



Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%
B_{inv}		$< 11\,\%$	$< 16\,\%$	

Nature 607, 52-59 (2022)

Nature 607, 60-68 (2022)

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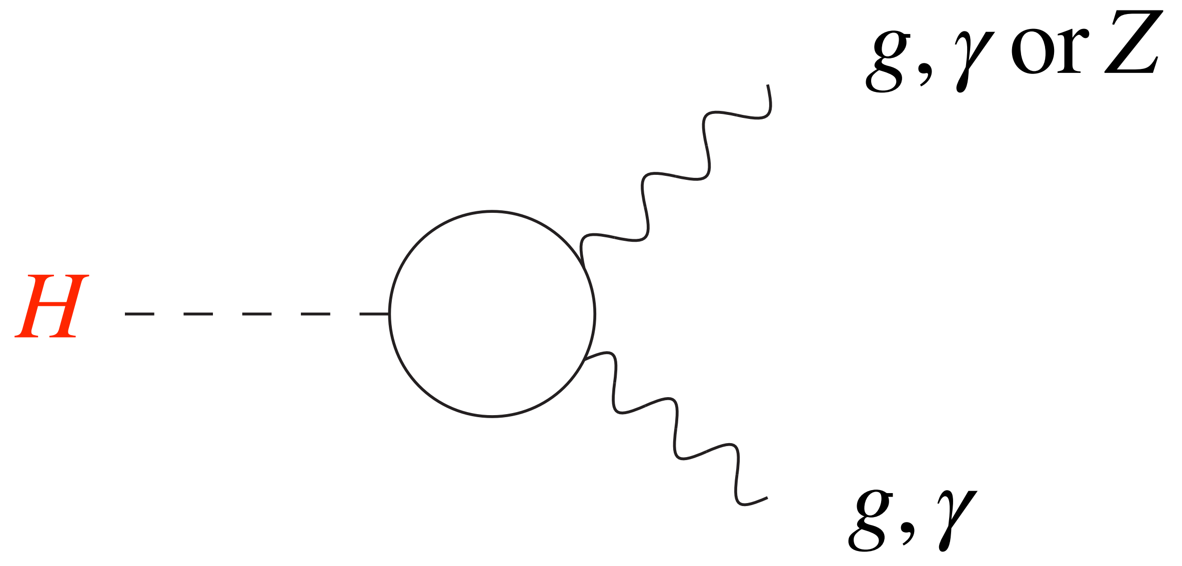
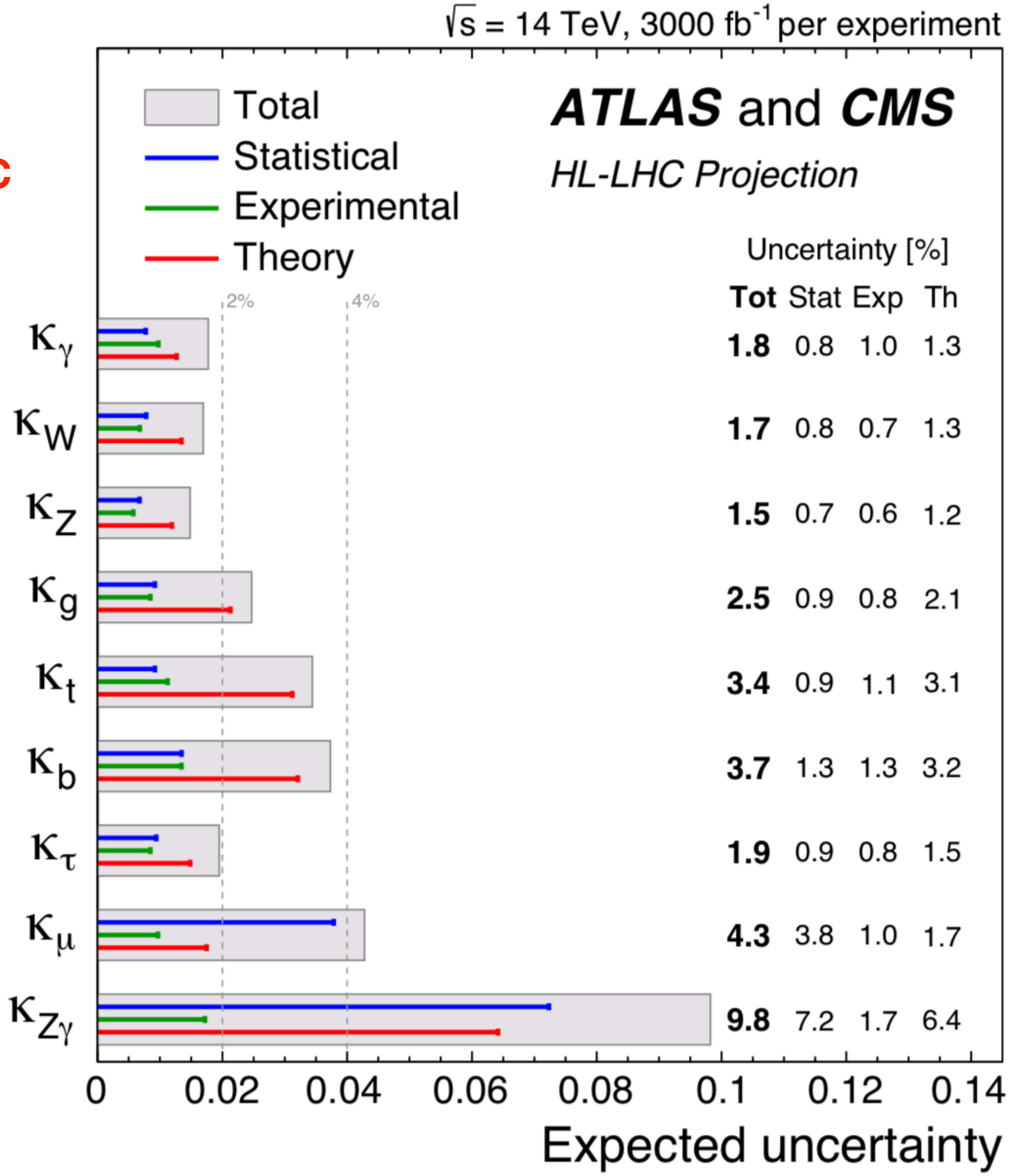
Probing new particles through loops



Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

TH Uncertainties dominant (assumed to be 1/2 of Run 2)

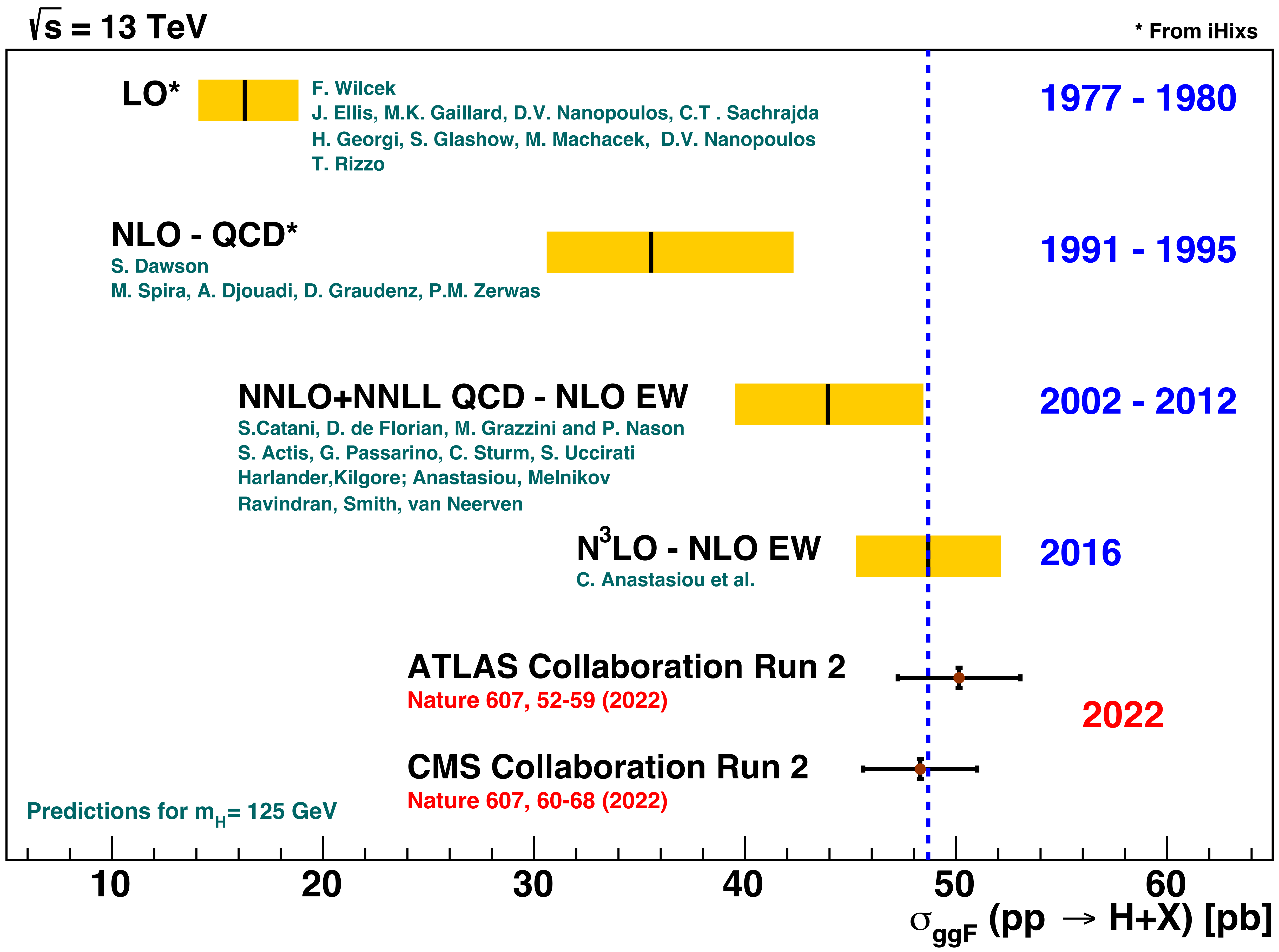
The Importance of Theory and Modelling

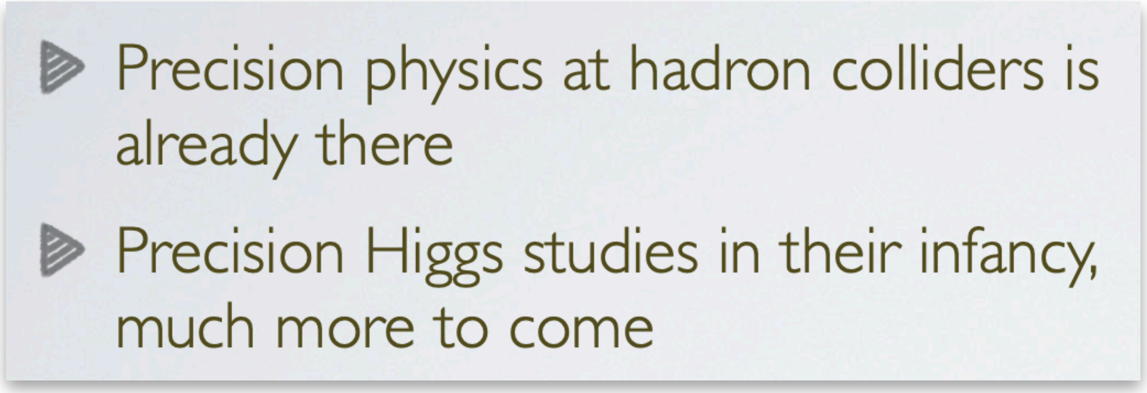
Predictions at hadron colliders are extremely complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…)

Most measurements at LHC are dominated by modelling and theory systematic uncertainties (with some notable exceptions).

The interpretability of our results relies on our ability to compute accurate and precise predictions!

The LHC has become a precision measurements machine, this would not have been possible without the efforts of the TH community.



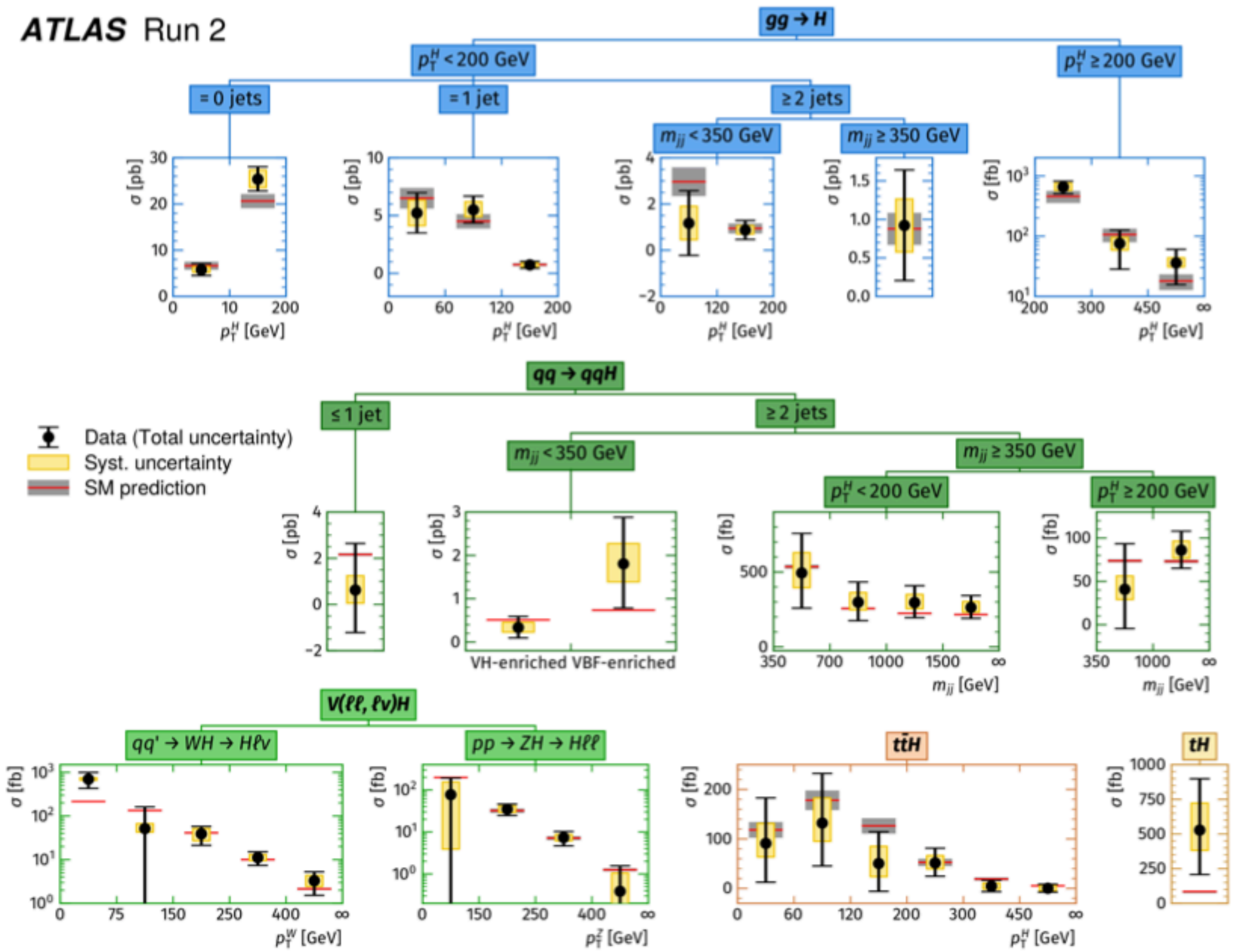


- Precision physics at hadron colliders is already there
- Precision Higgs studies in their infancy, much more to come

See talk by **Giulia** (Bormio 2018) on precision at LHC!

Exploring further with STXS and SMEFT Interpretations

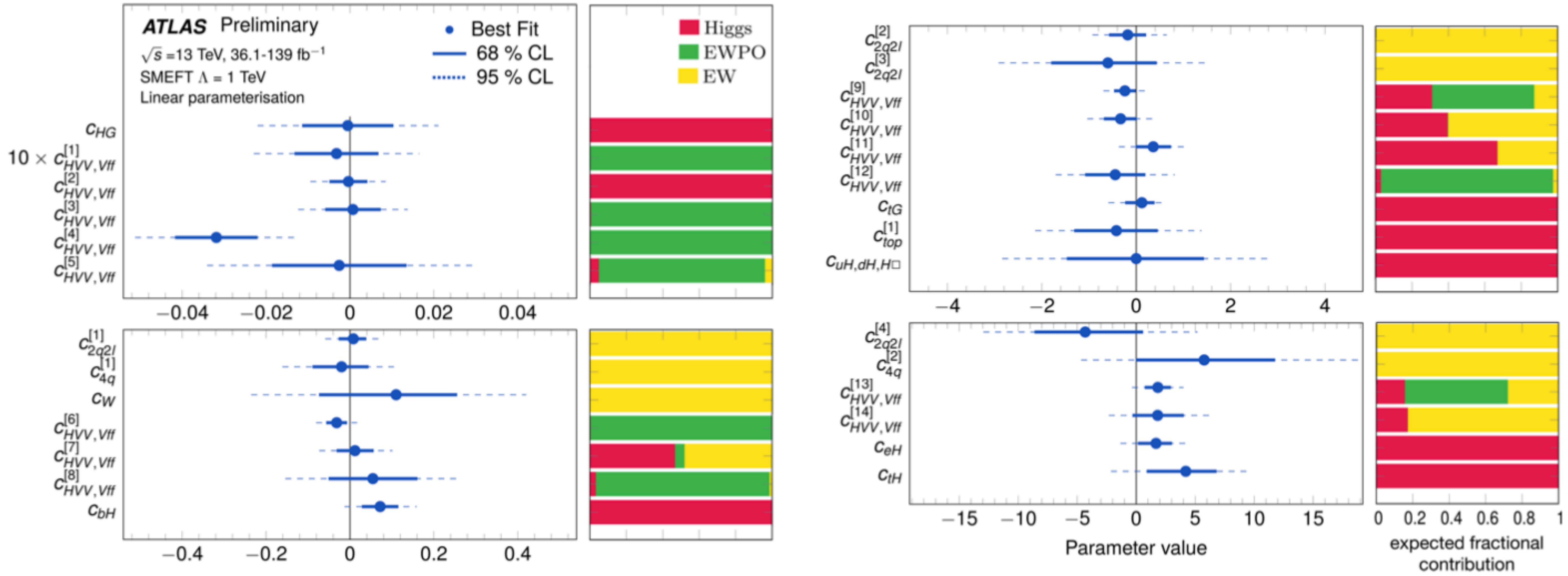
Simplified Template Cross Sections (STXS): Combined measurements of Higgs boson production and decay in exclusive kinematic regions of the production phase space (and different production processes).



Interpretation in **Standard Model** (only SM fields) **Effective Field Theory** (**SMEFT**): Electroweak precision data on the Z resonance from LEP and SLC.

SMEFT is a coherent tools to interpret our data, it is key given that the no new physics has been directly found at the LHC.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots .$$



The Size of The Higgs boson

How to read these results?

One important example, is the $\mathcal{O}_H$ operator which represents the leading interaction term for a composite Higgs boson

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

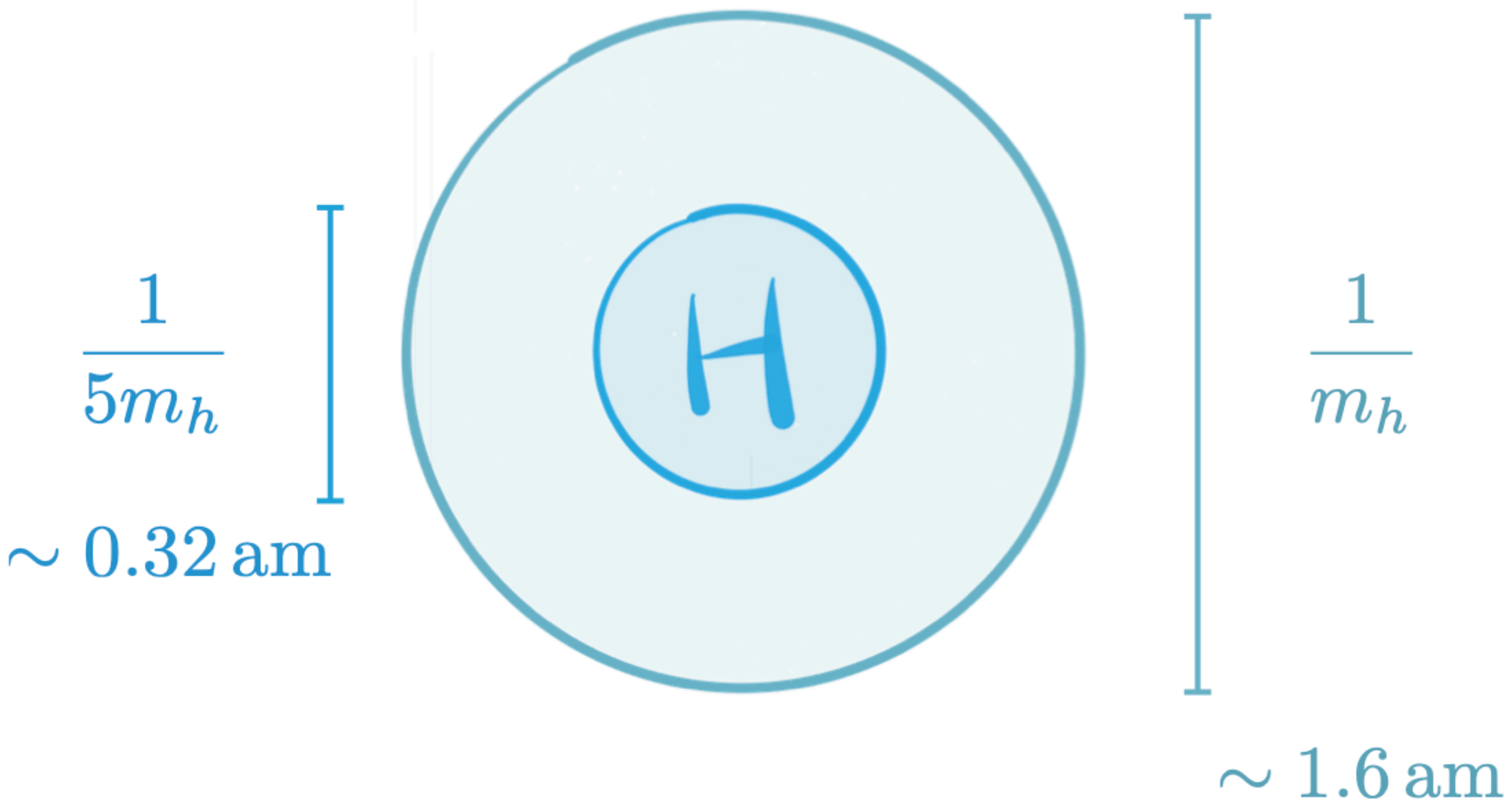
After EW symmetry breaking it normalises the kinetic term in the Lagrangian and thus **modifies all couplings simultaneously!**

$$\frac{c_H}{\Lambda^2} \cdot \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \rightarrow \left(\frac{2 c_H v^2}{\Lambda^2}\right) \cdot \frac{1}{2}\left(\partial_\mu h\right)^2$$

$$c_H \frac{v^2}{\Lambda^2} < 0.06$$

Taking $c_H = 1$ leads to $\Lambda > 1$ TeV

Comparing the Compton radius of the Higgs $1/m_H$ to its radius $1/\Lambda$ (as comparing the mass of the pion to that of the ρ meson!



The Higgs could very well be a pNGB as the pion!

More precision is needed to probe the compositeness of the Higgs boson!!

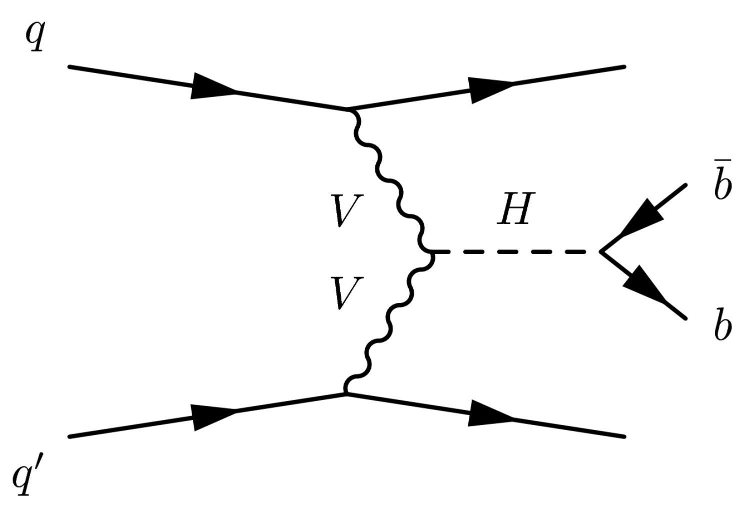
“A case for future lepton colliders” N. Craig (See paper)

Run 2 Highlights and Run 3 Milestones

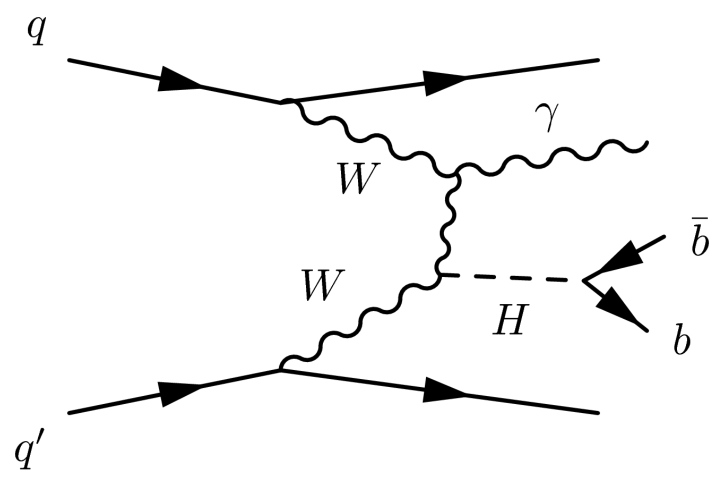
Higgs boson decays to b-quarks in VBF Production

EPJC 81 (2021)

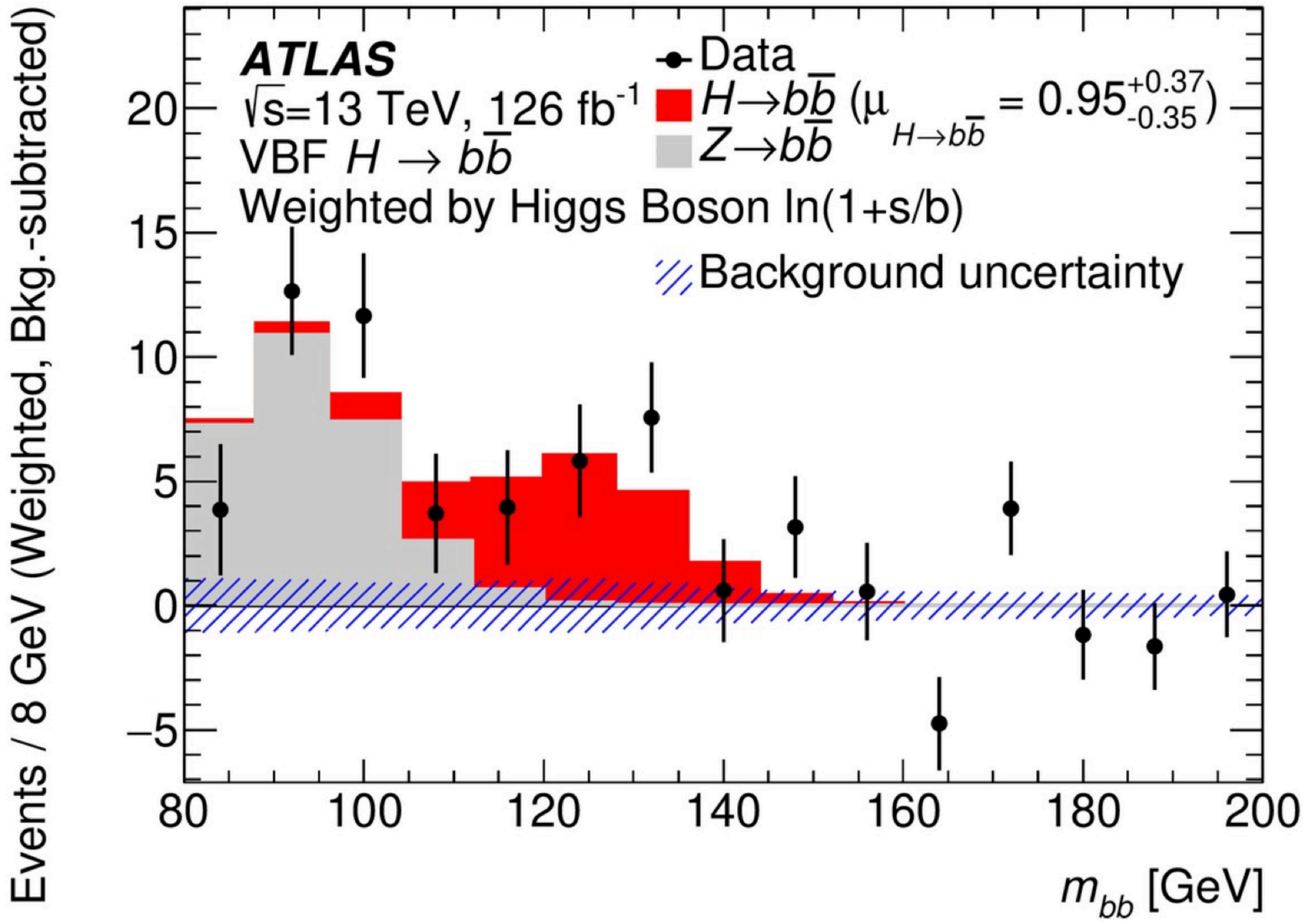
VBF analysis with Higgs in bb including channel with photon

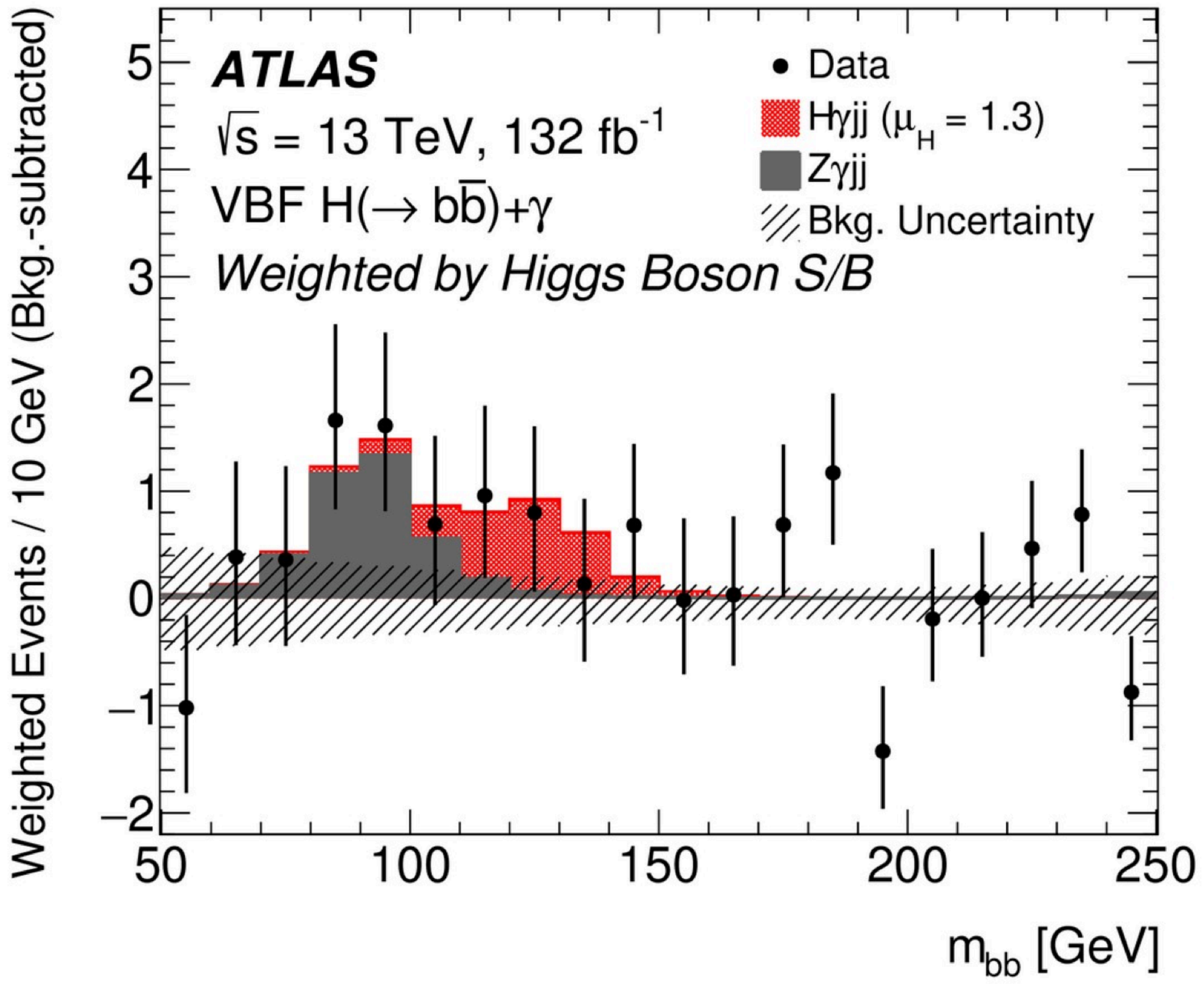


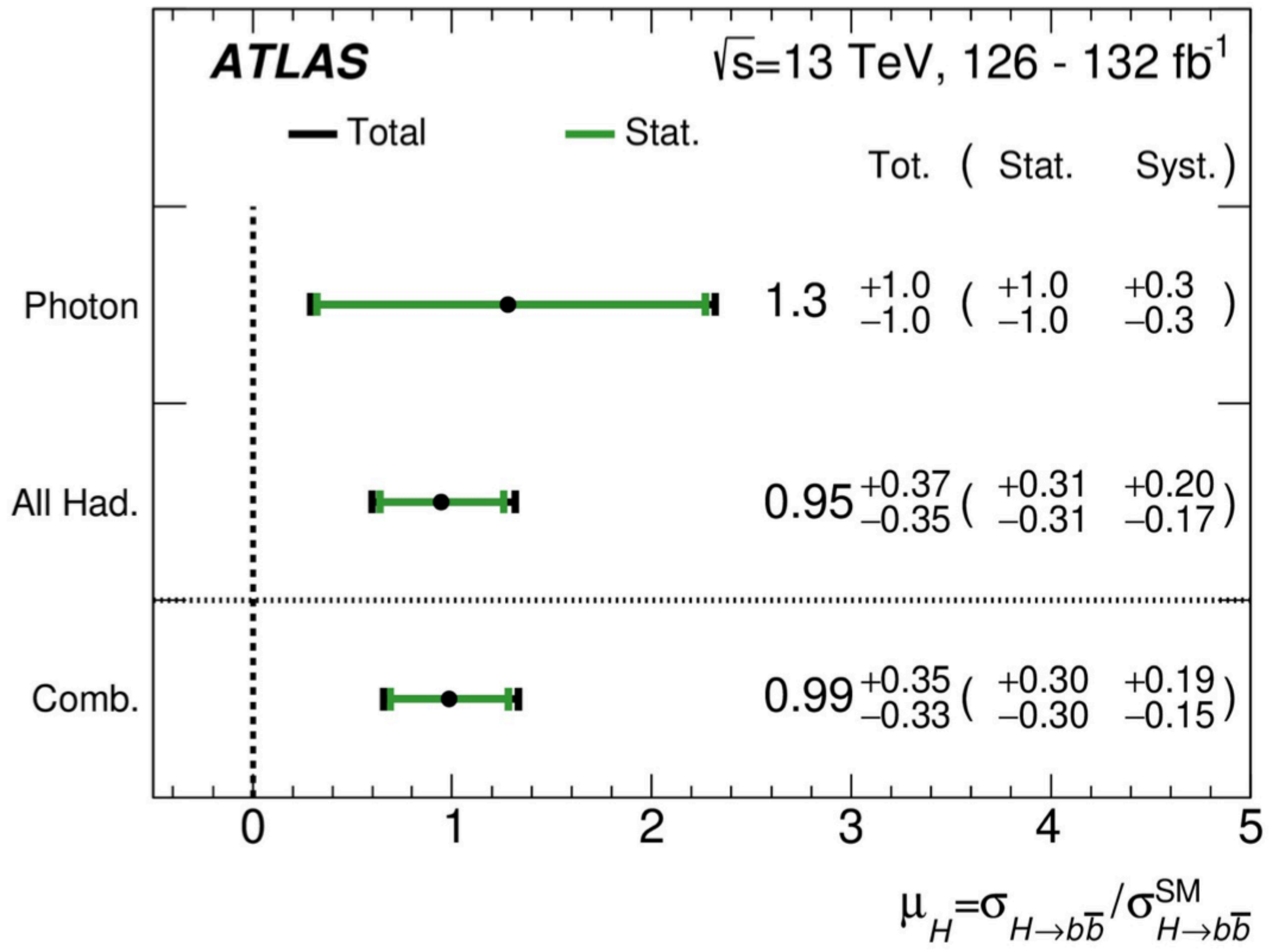
Non trivial trigger requirements!



Taking advantage of the VBF with a photon topology which reduces significantly QCD background which has a destructive interference! It is also very useful to trigger on.



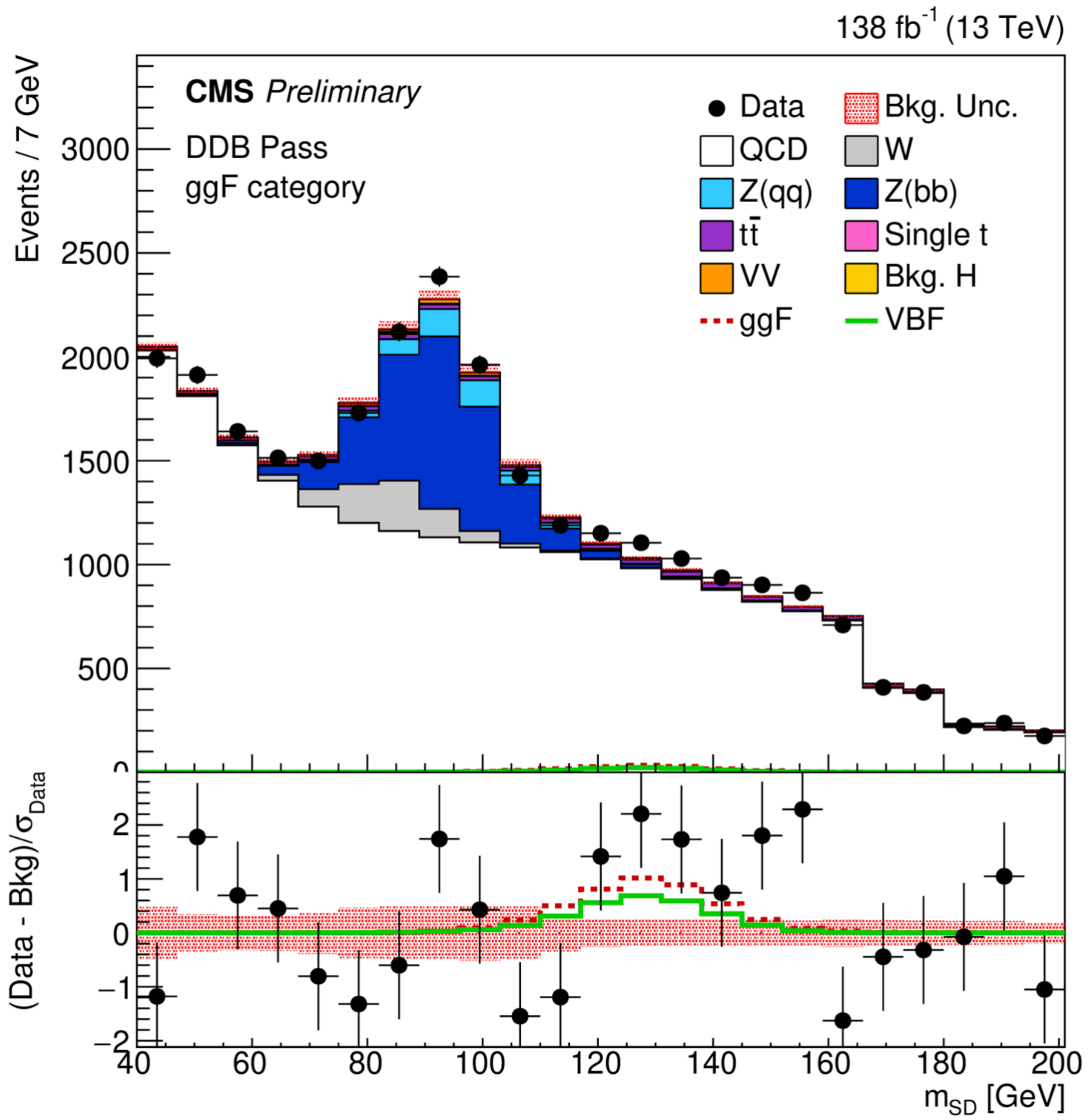


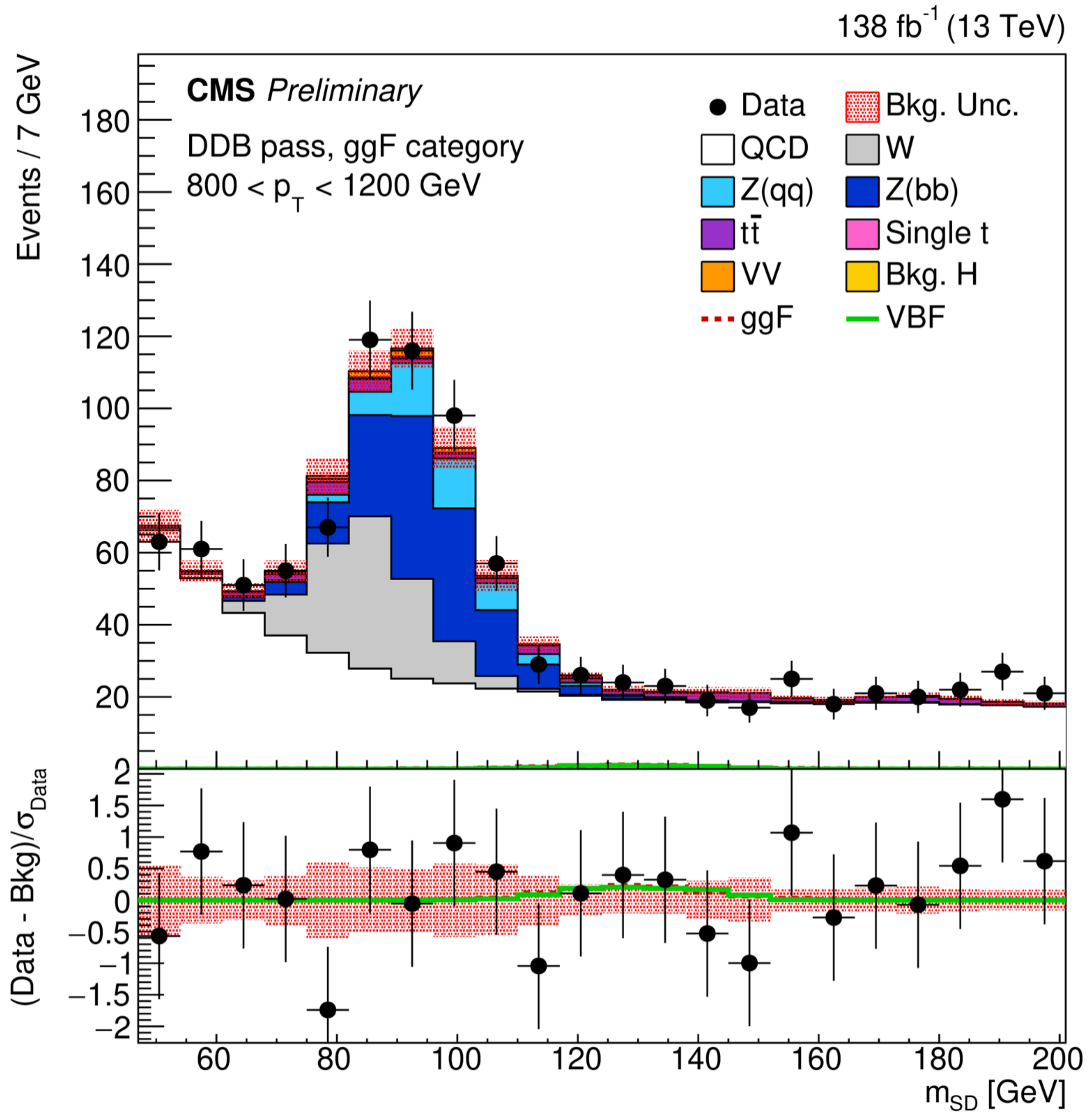


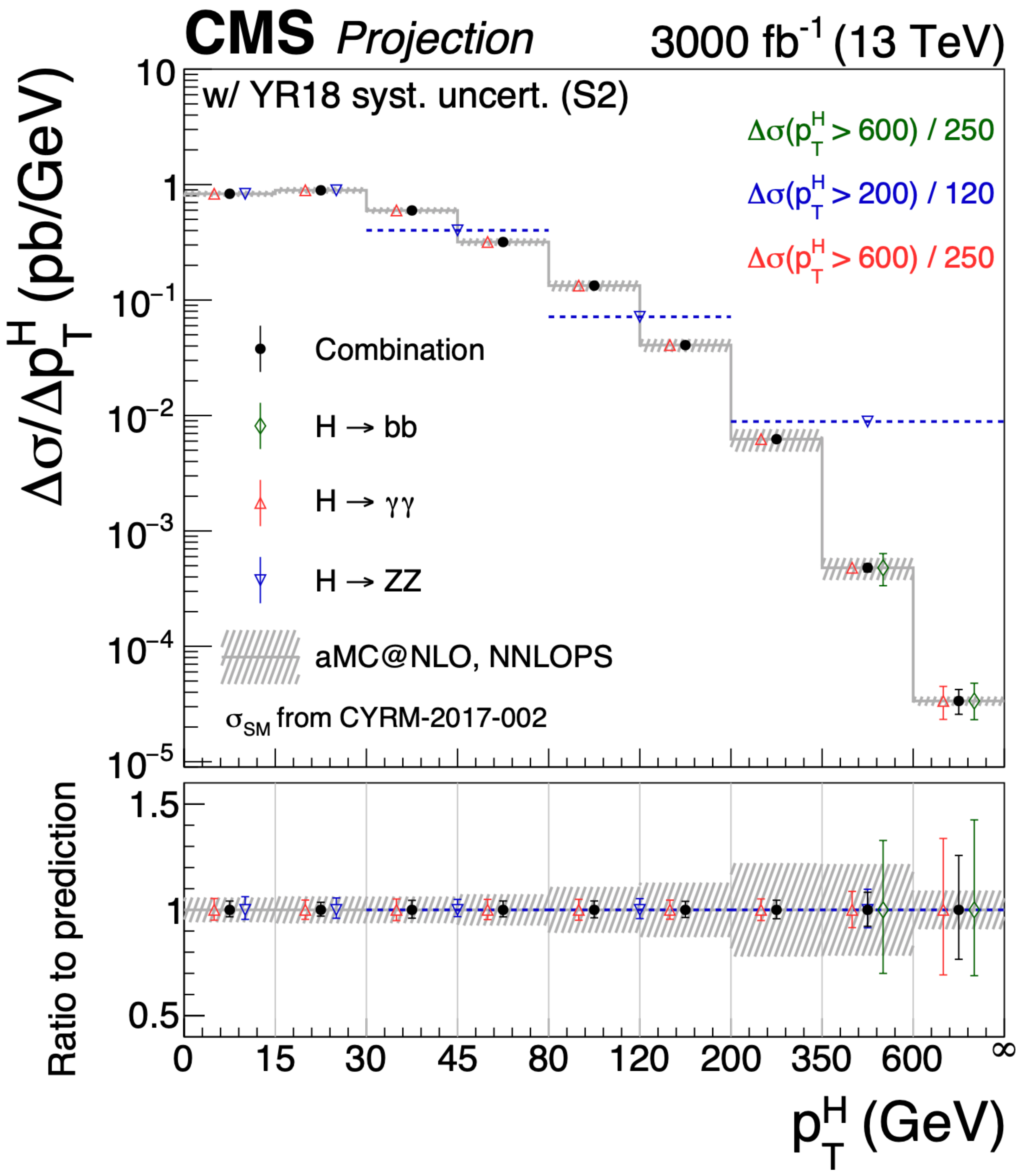
3.0σ (3.0σ expected)

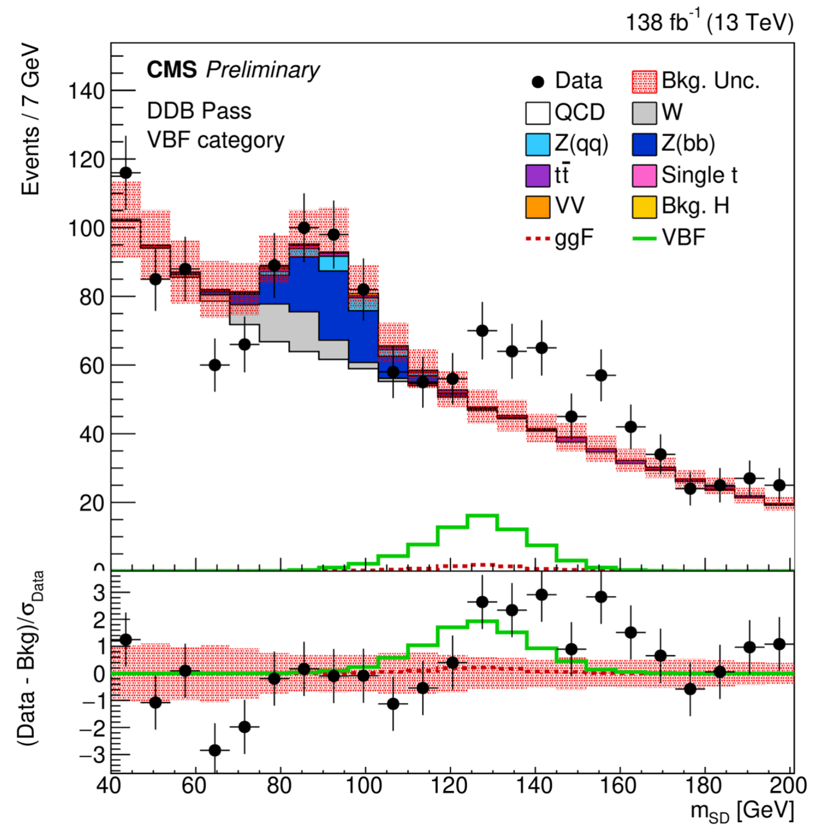
Evidence!

Boosting the Higgs Boson!









Was thought to be completely impossible!

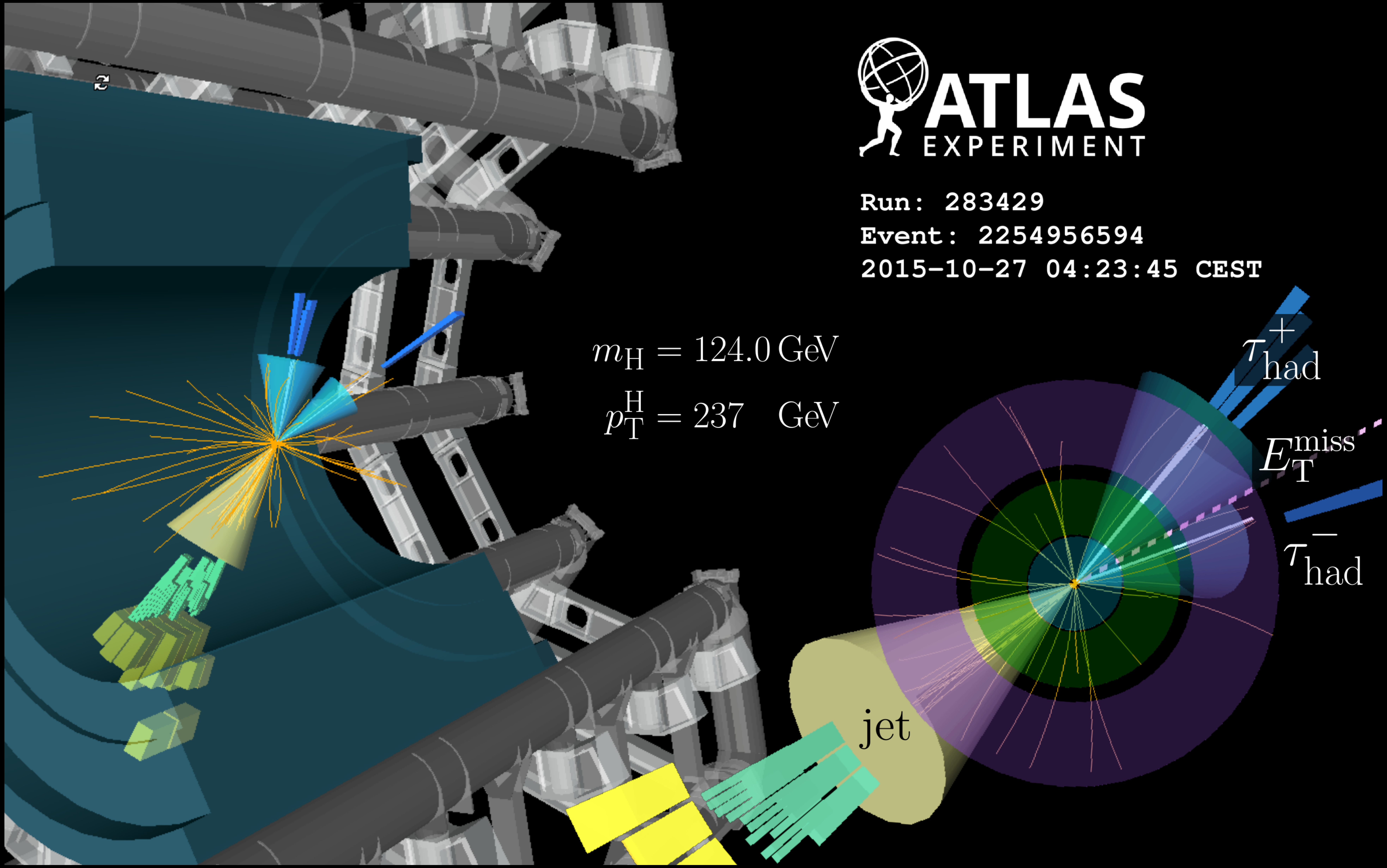
VBF significance is 3.0 σ (0.9 σ)

ggF significance of 1.2 σ (0.9 σ)

It can play an important role in the measurements of the inclusive production at high transverse momentum!

Extremely interesting for indirect NP constraints!

Higgs Yukawa to taus CP Properties



CP properties of the tau Yukawa through polarisation correlations in $H \to \tau^+\tau^-$ decay

Boosted $H \to \tau^+\tau^-$ candidate event

Higgs Yukawa to taus CP Properties

The CKM sector CP violation is insufficient for baryogenesis, pseudoscalar coupling of the Higgs boson to fermions could be an important source of CP violation!

$$\frac{\lambda_f}{\sqrt{2}}\left(\kappa_f h\overline{\psi}_f\psi_f + i\tilde{\kappa}_f h\overline{\psi}_f\gamma_5\psi_f\right)$$

Non zero $\tilde{\kappa}_f$ implies CP violation in the Yukawa interaction

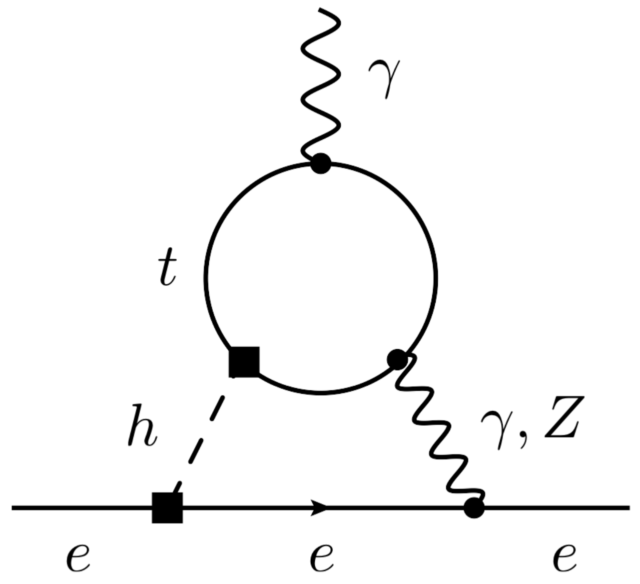
However indirect probes through electron (and neutron) EDM
Very suppressed in the SM (where it arises at four loops)

$$d_e/e < 10^{-38}\ \text{cm}$$

Larger if neutrinos are Majorana

A good probe for NP BSM!

Careful, constraints from eEDM are already strong! From J. Brod., U. Haisch and J. Zupan 2013



$$\frac{d_e}{e} \propto G_F m_e \left[C_1\kappa_e\tilde{\kappa}_t + C_2\tilde{\kappa}_e\kappa_t\right]$$

$$\uparrow$$

$$f\left(\frac{m_t^2}{m_h^2}\right)$$

ACME II limit: $\left|\frac{d_e}{e}\right| < 1.1\ 10^{-29}\ \text{cm}$

Assuming electron Yukawa SM $\tilde{\kappa}_t < 0.001$

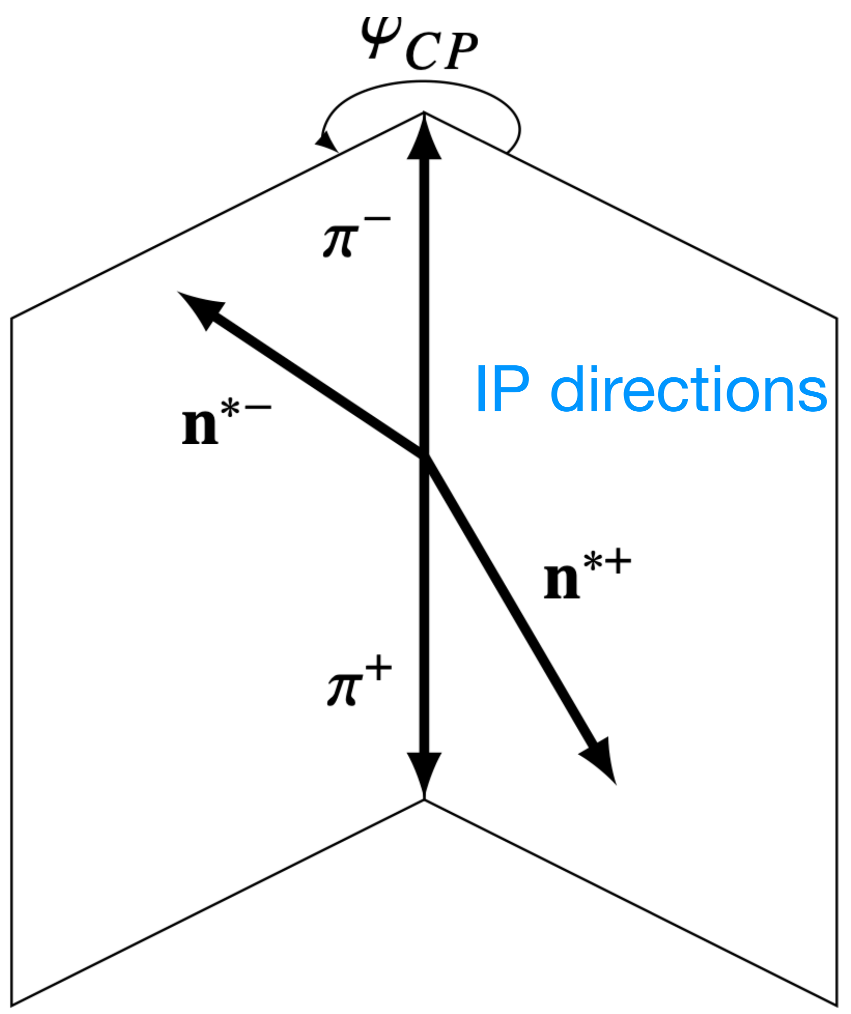
The electron EDM constraint is weaker for taus $\tilde{\kappa}_\tau < 0.3$

First attempts to constrain this coupling using tau polarisation observables

Higgs Yukawa to taus CP Properties

Use tau polarisation variables in tau decays of the Higgs boson!

$$H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$$



Zero Momentum Frame

IP directions

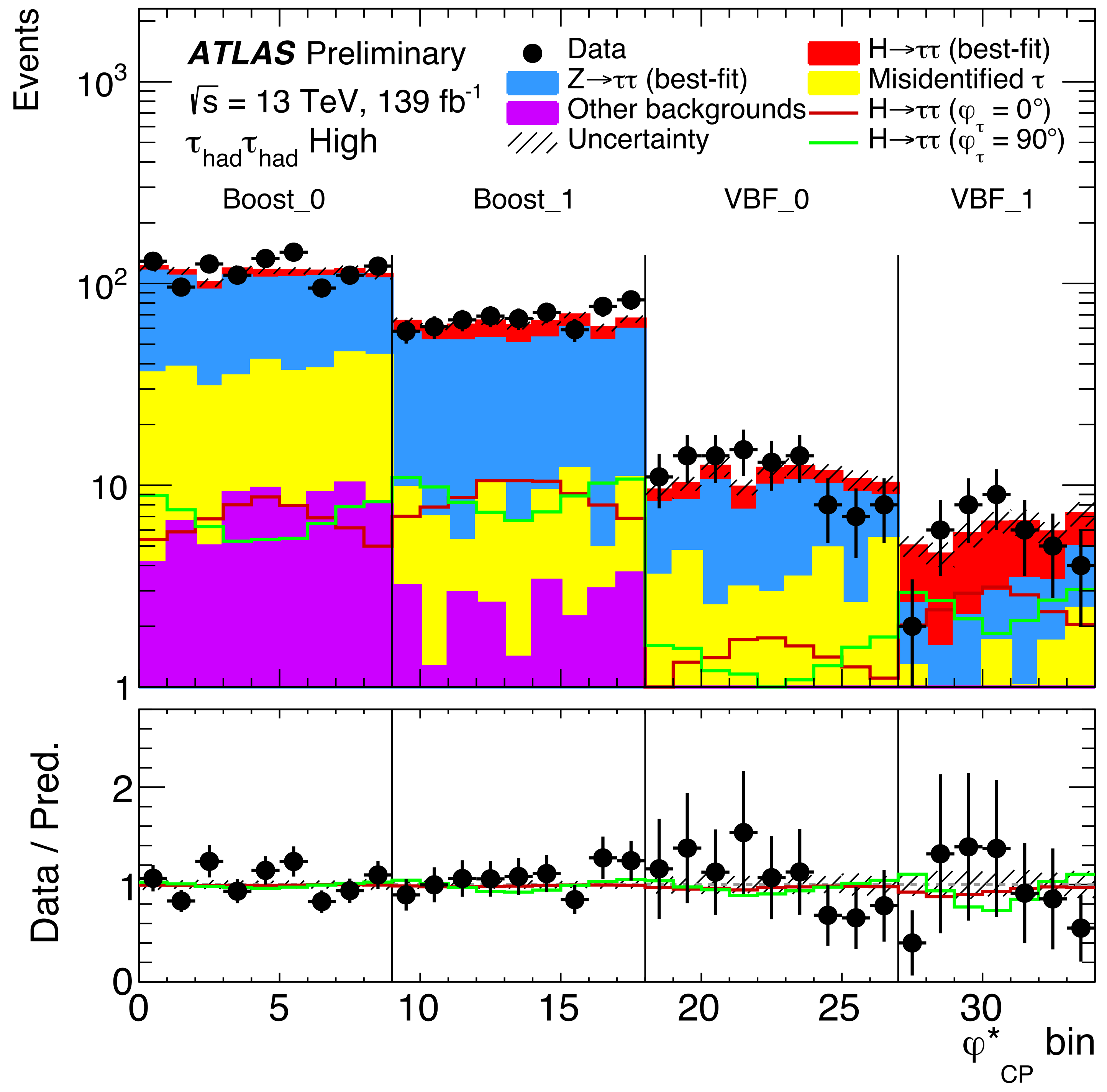
Tau transverse spin correlation sensitive variable

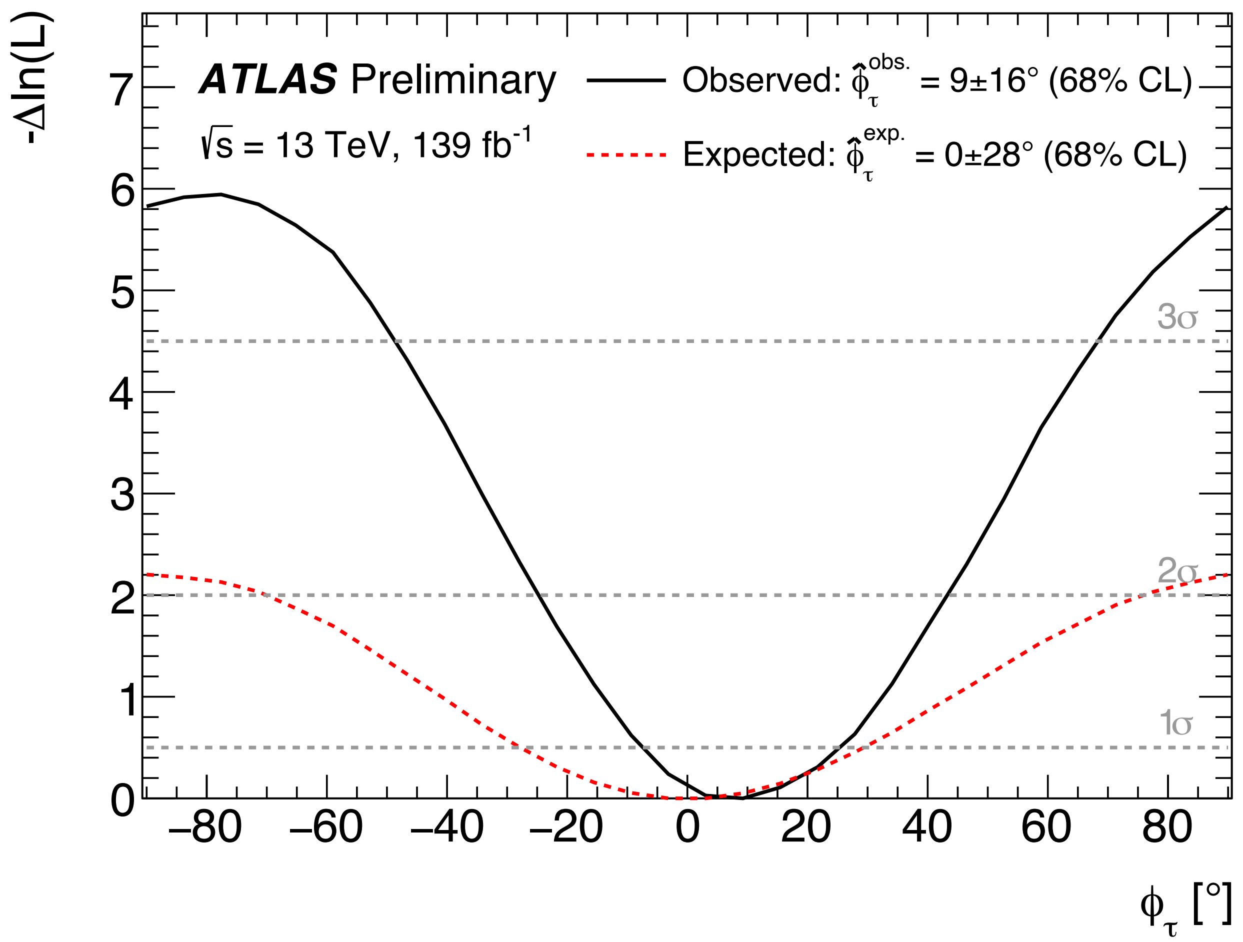
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Fit the ϕ_τ parameter to the ϕ^*_{CP}

Using several decay modes of the taus

Boosted and VBF (using a BDT) categories

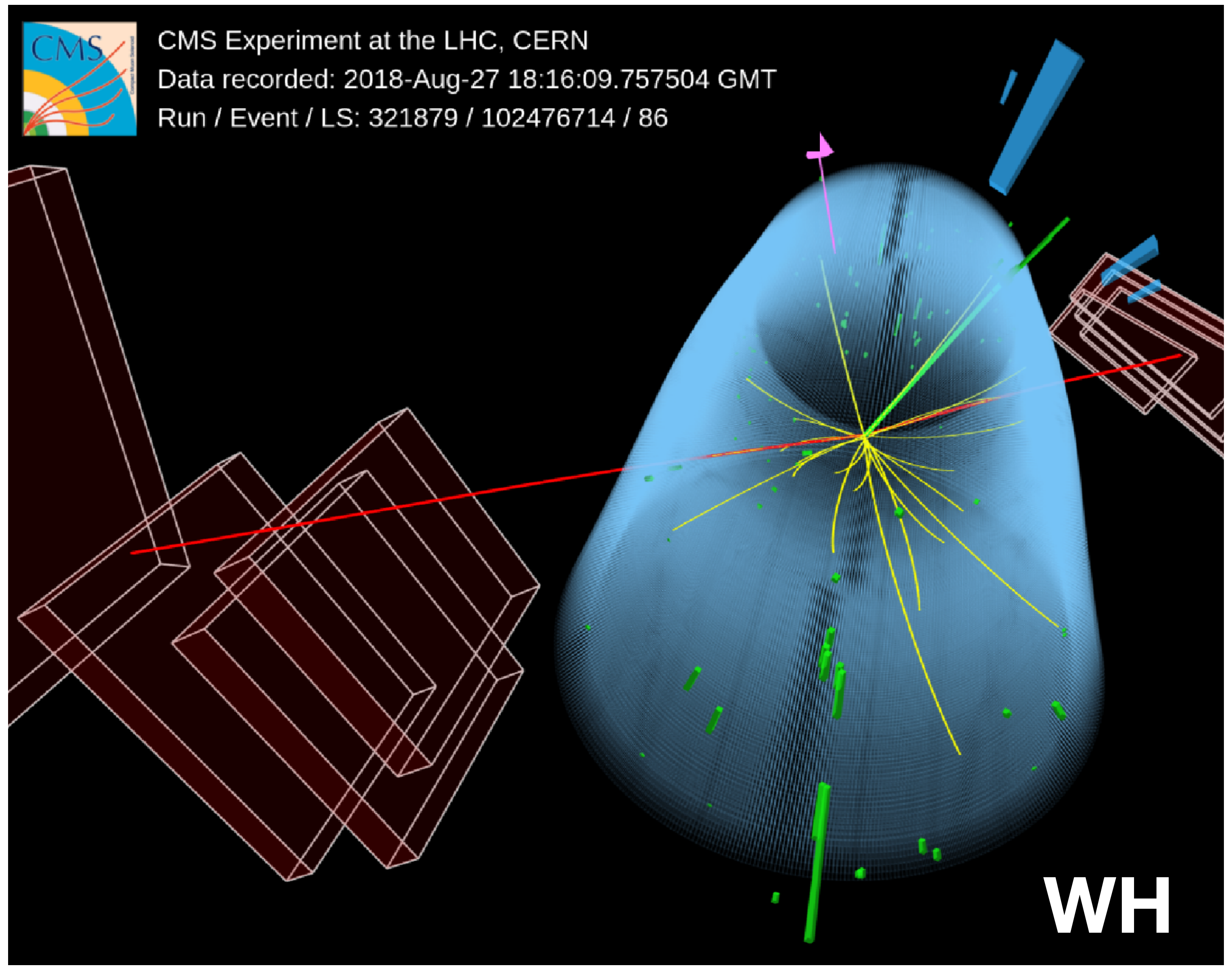


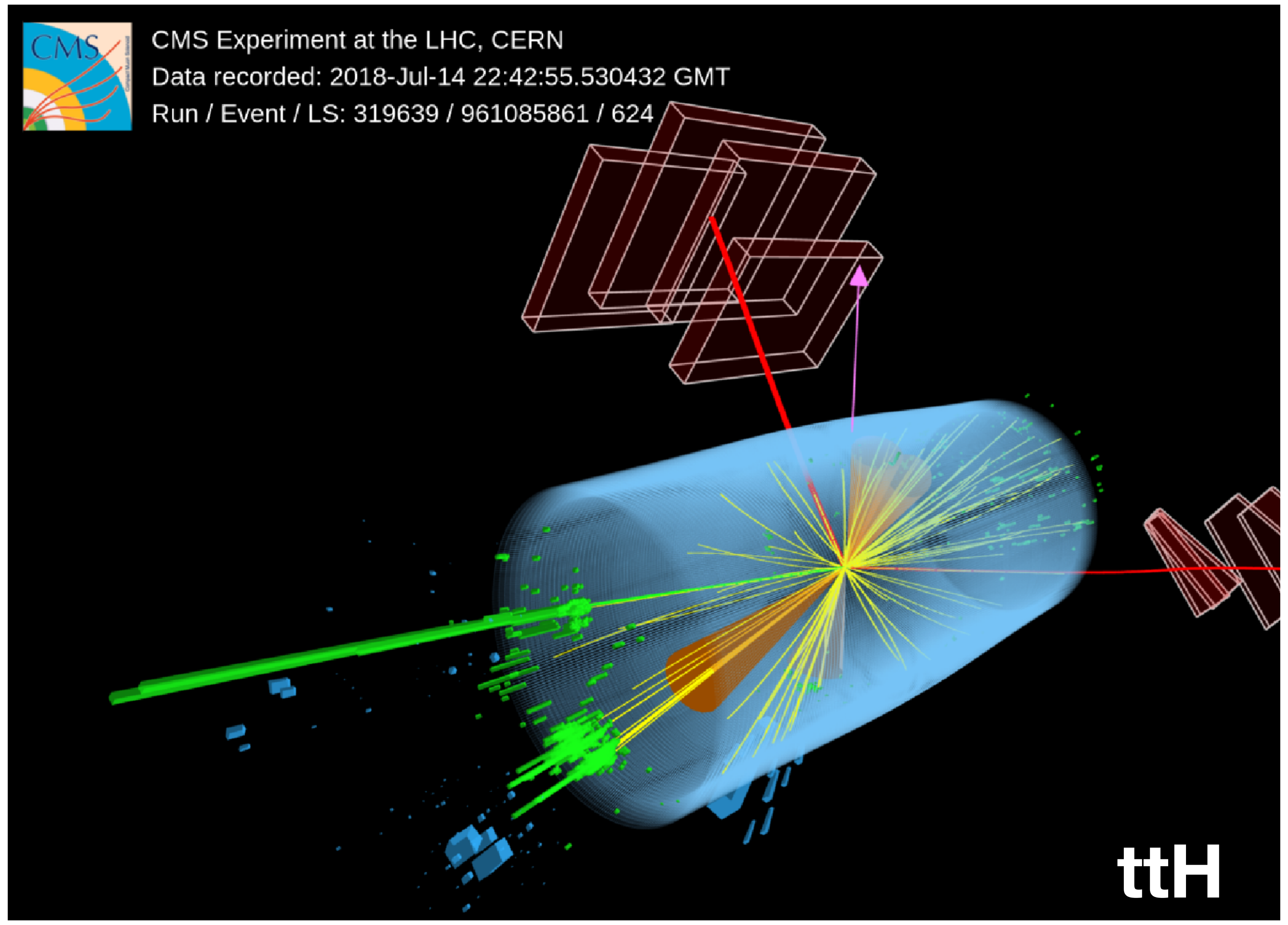


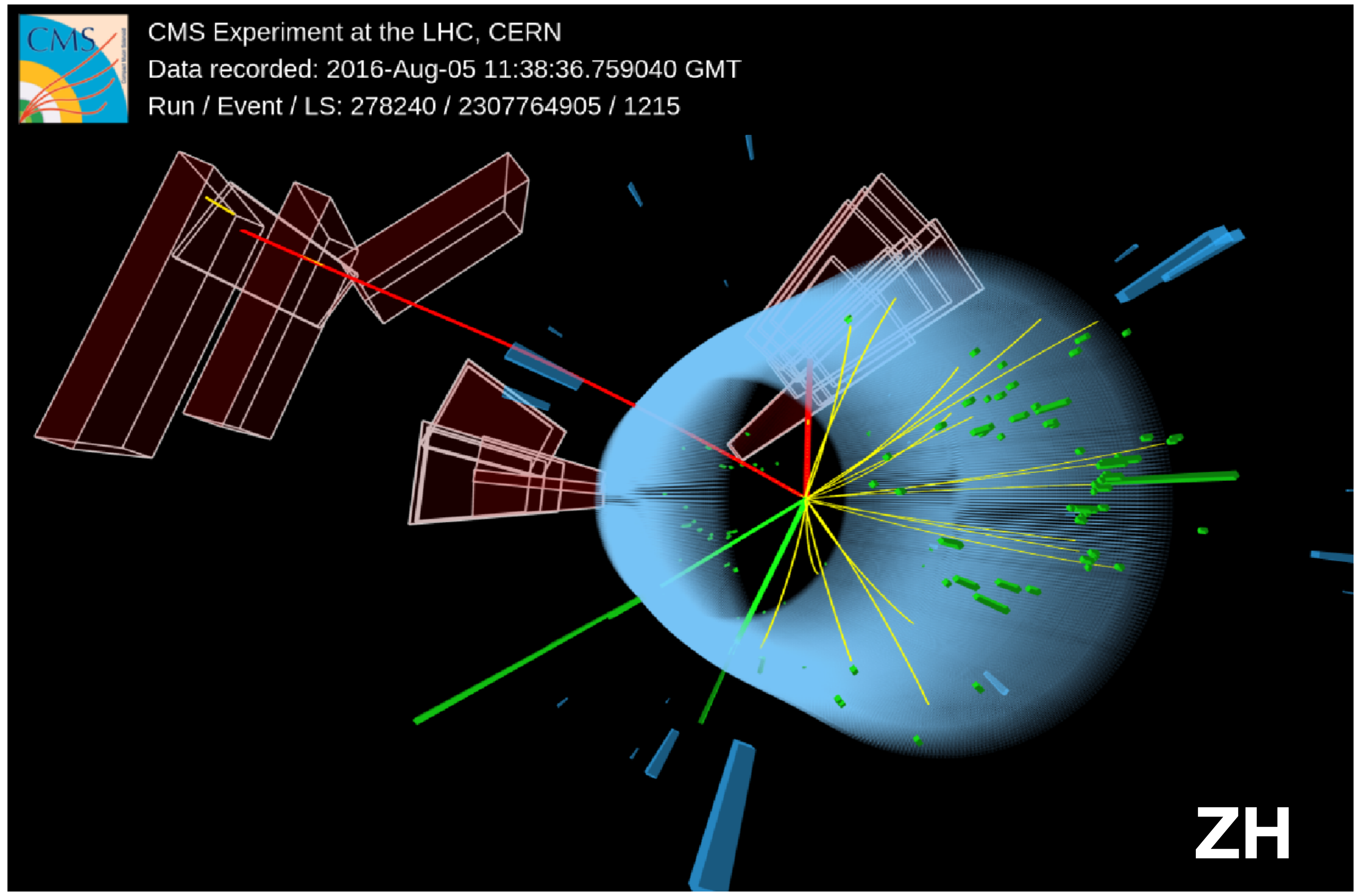
Pure CP-Odd hypothesis excluded at 3.4σ

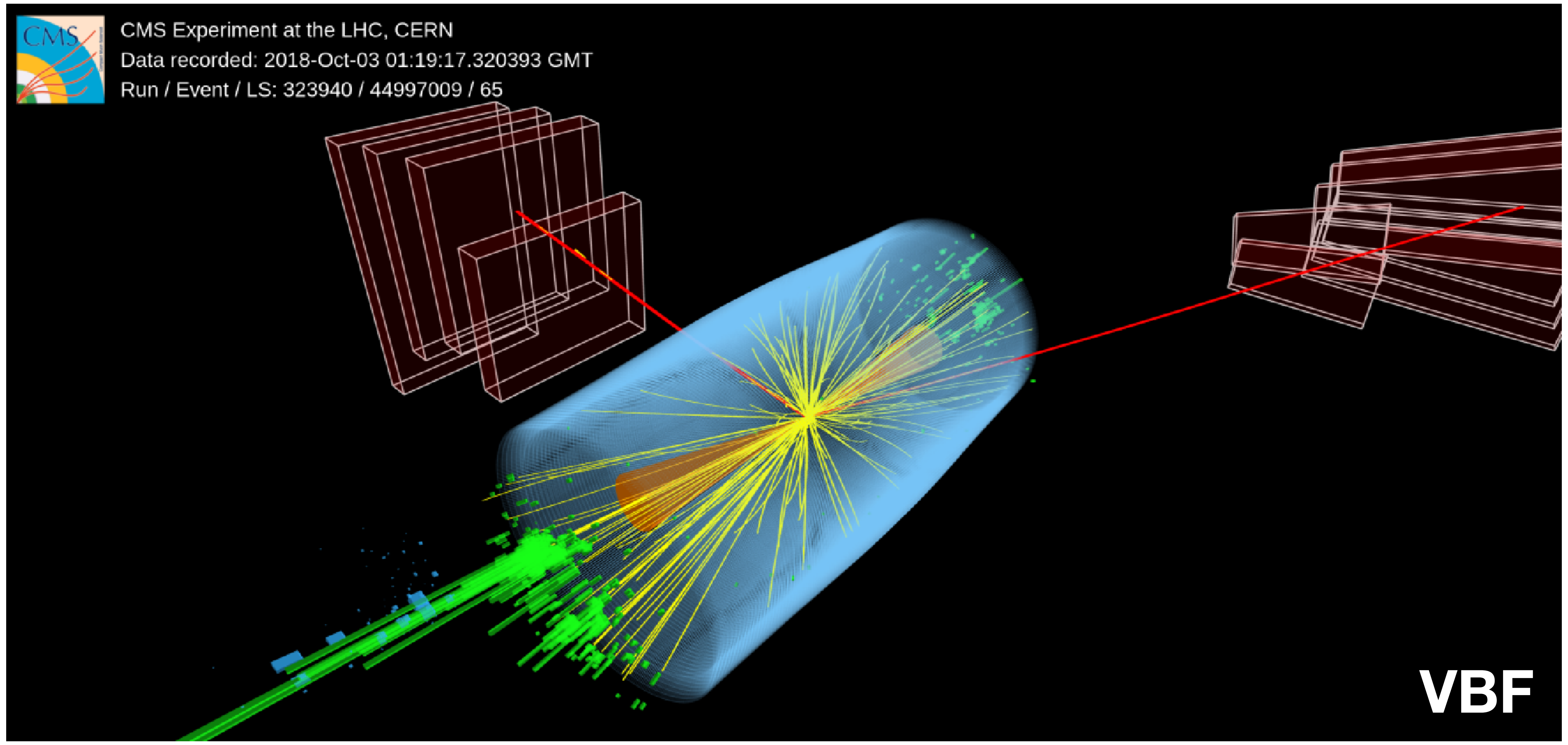
$$\boxed{\phi_\tau = 9^o \pm 5^o(\text{sys}) \pm 16^o(\text{stat})}$$

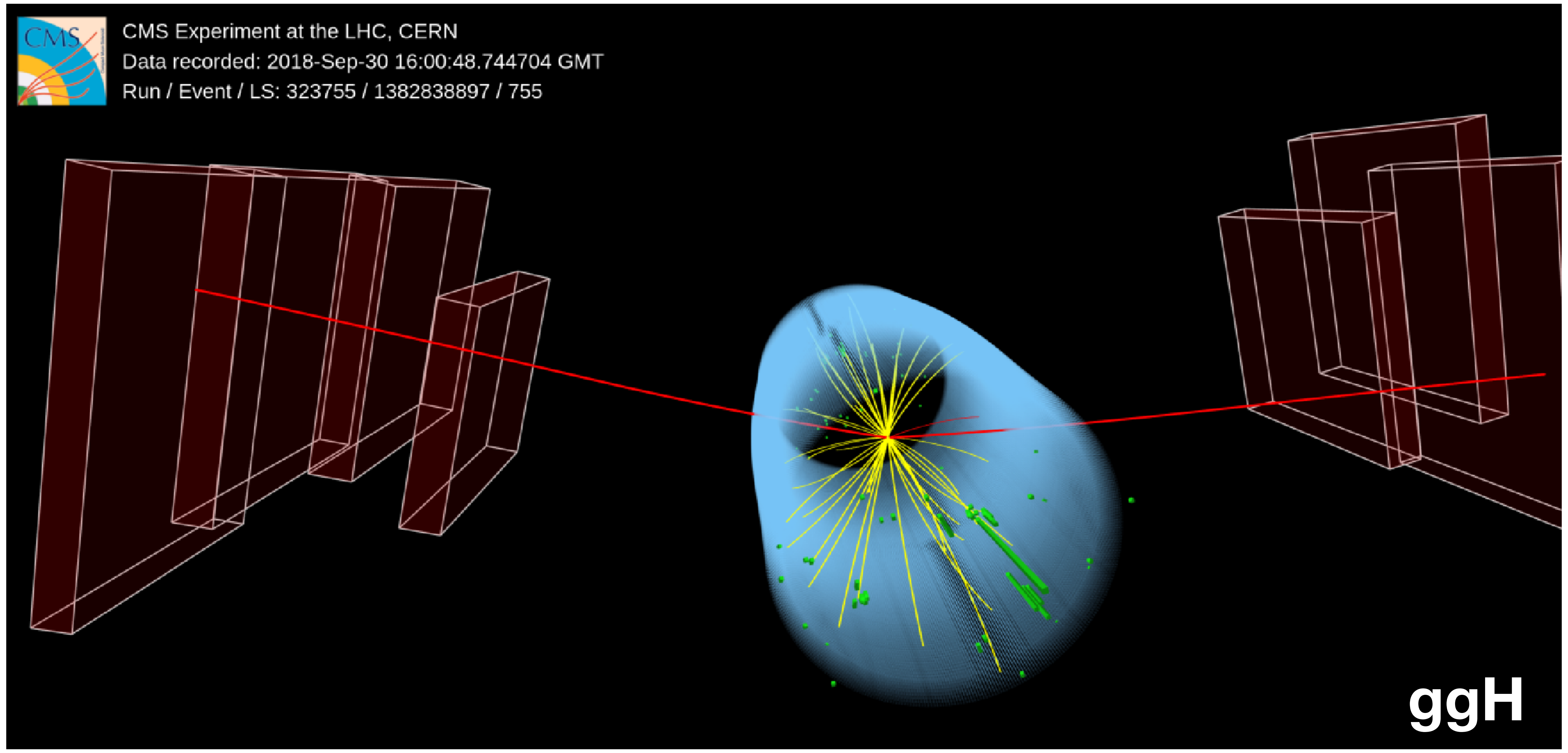
Evidence for $H \to \mu^+\mu^-$









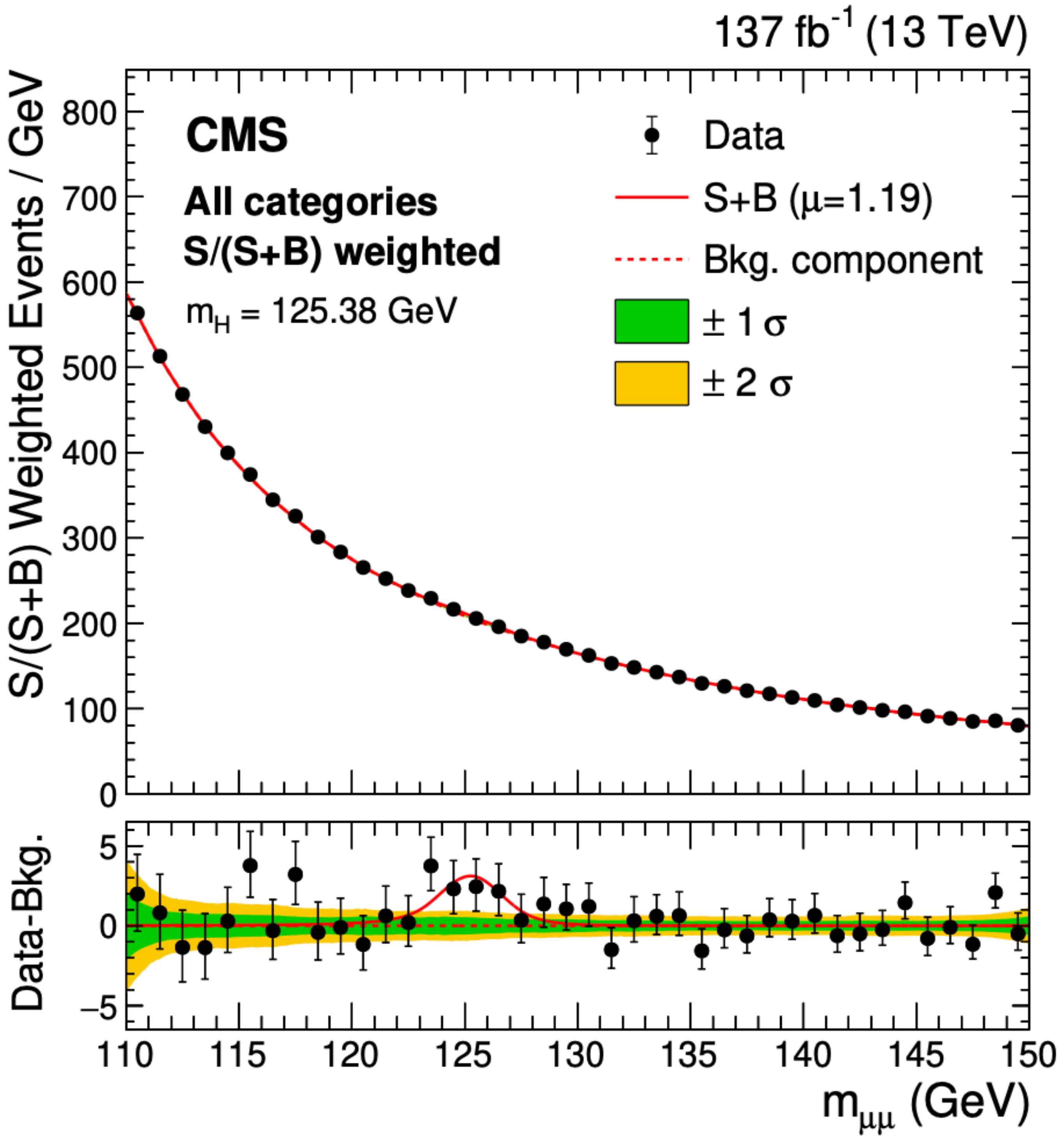


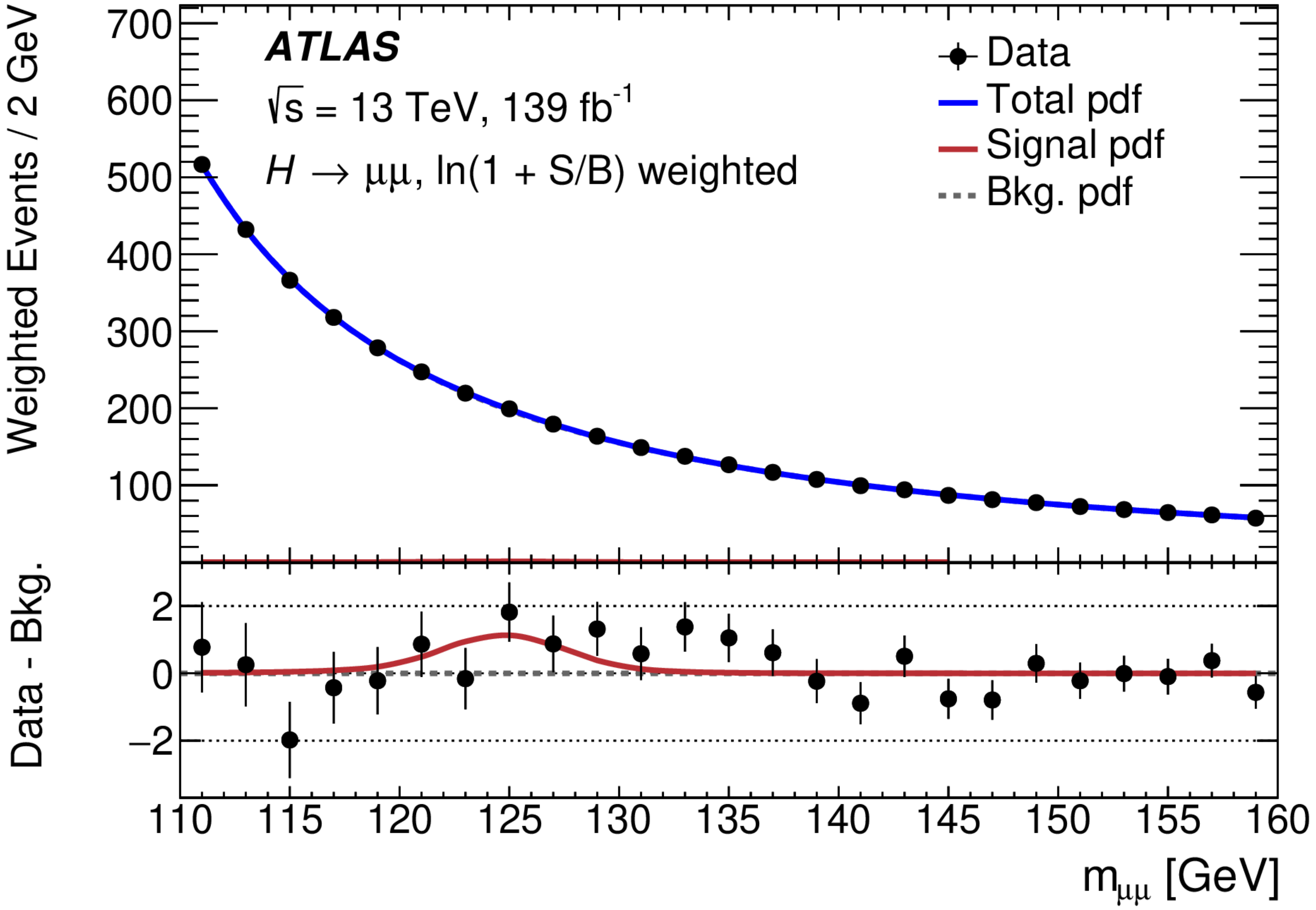
Evidence for Second Generation Yukawa Coupling

Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity: ggF, VBF, VH, ttH; mass resolution through Brem recovery!

Summary of all categories Estimate the background parameters through a fit of an analytical form!





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Summary of all categories Estimate the background parameters through a fit of an analytical form!

CMS Result

Expected 2.5σ

Observed 3.0σ

$$\mu = 1.19 \pm 0.43$$

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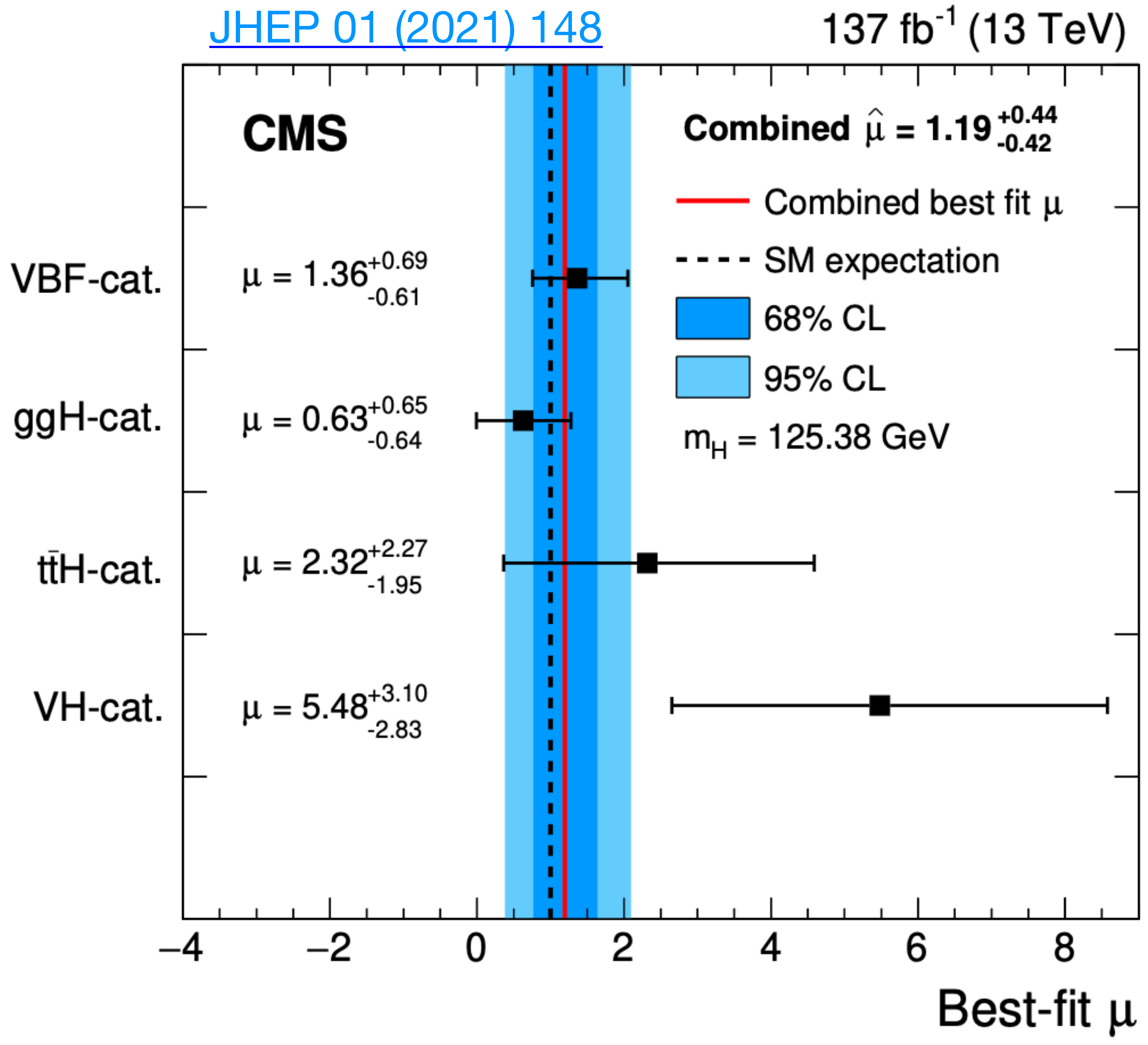

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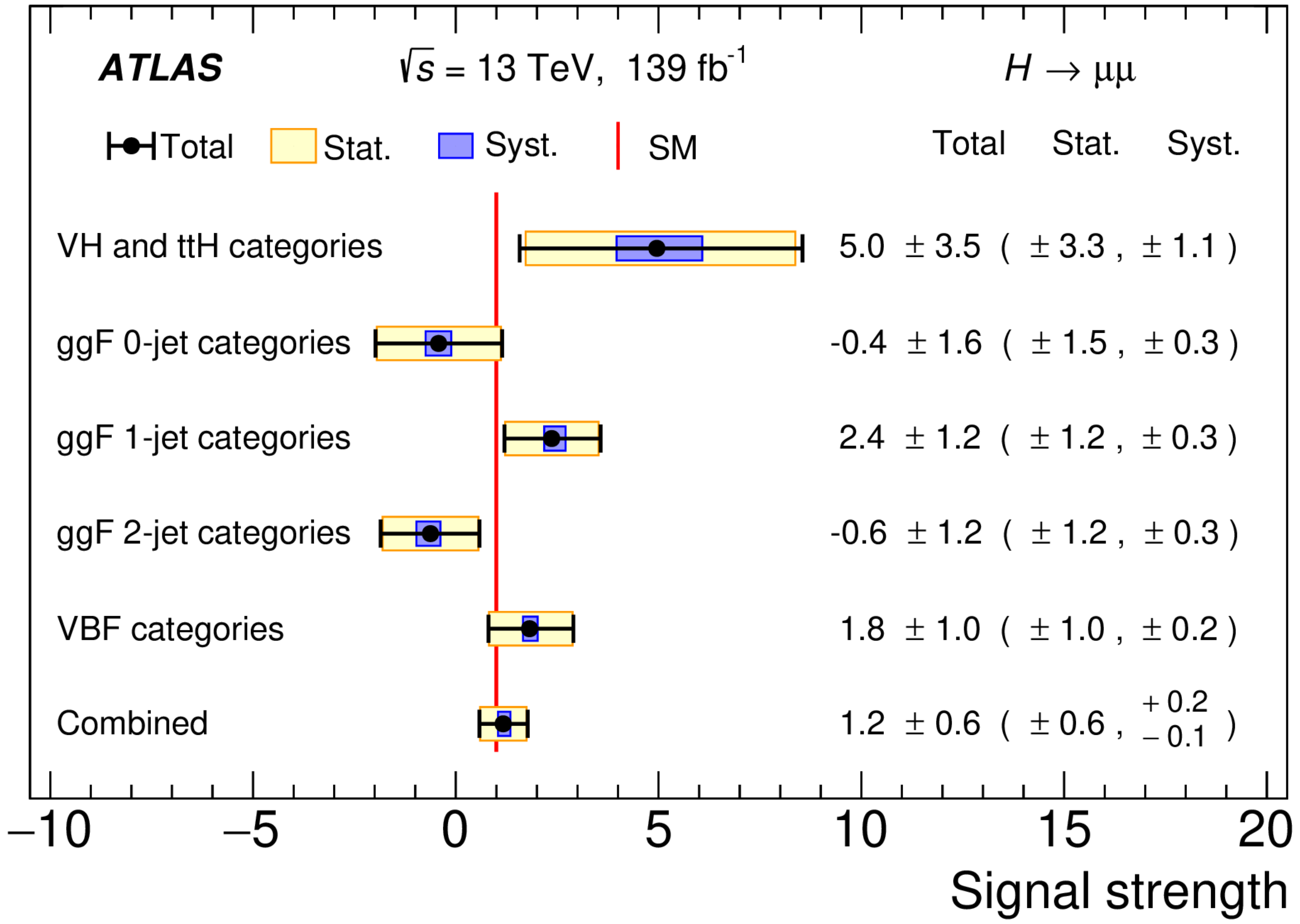


ATLAS Result

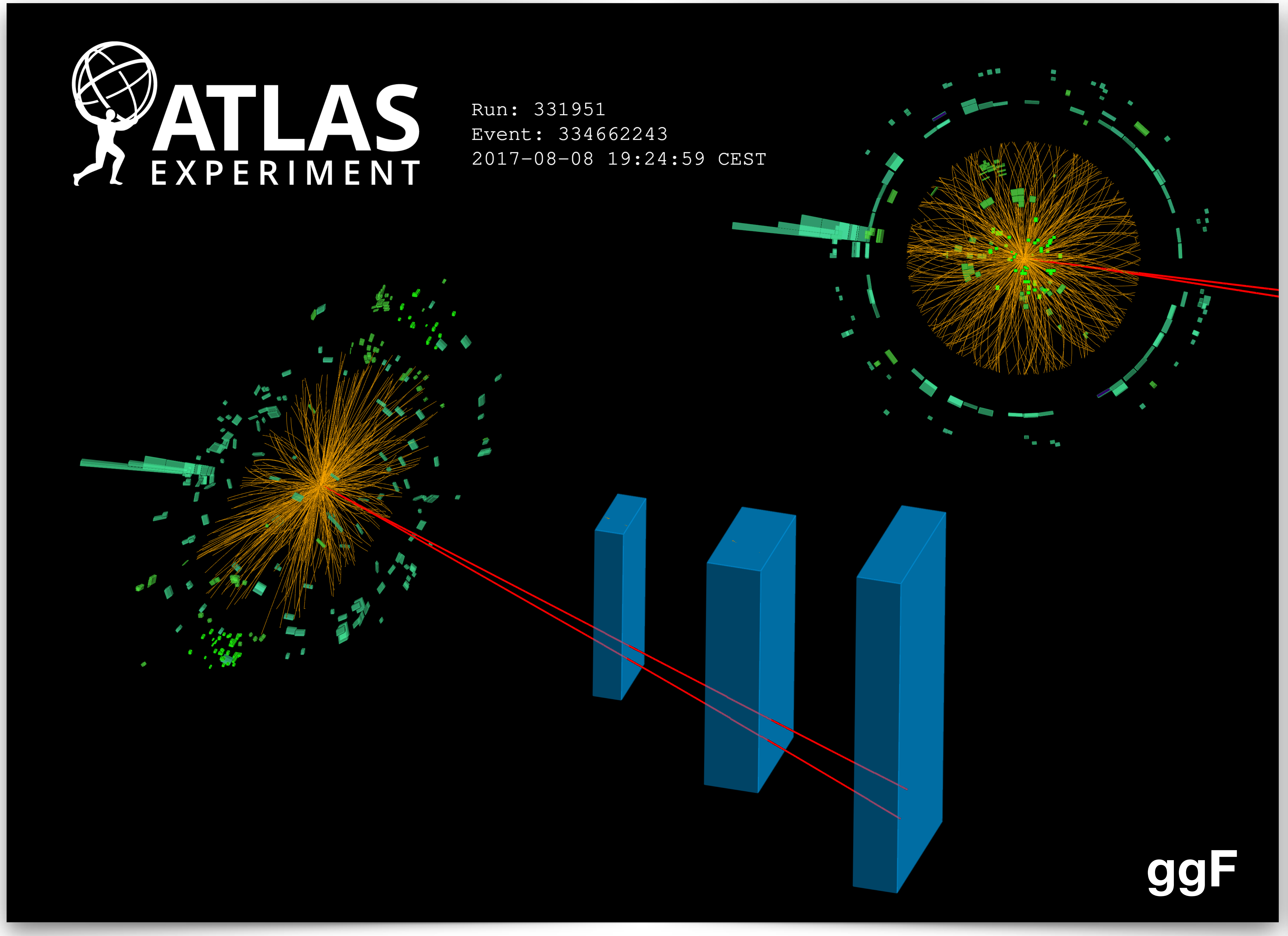
Expected 1.7σ

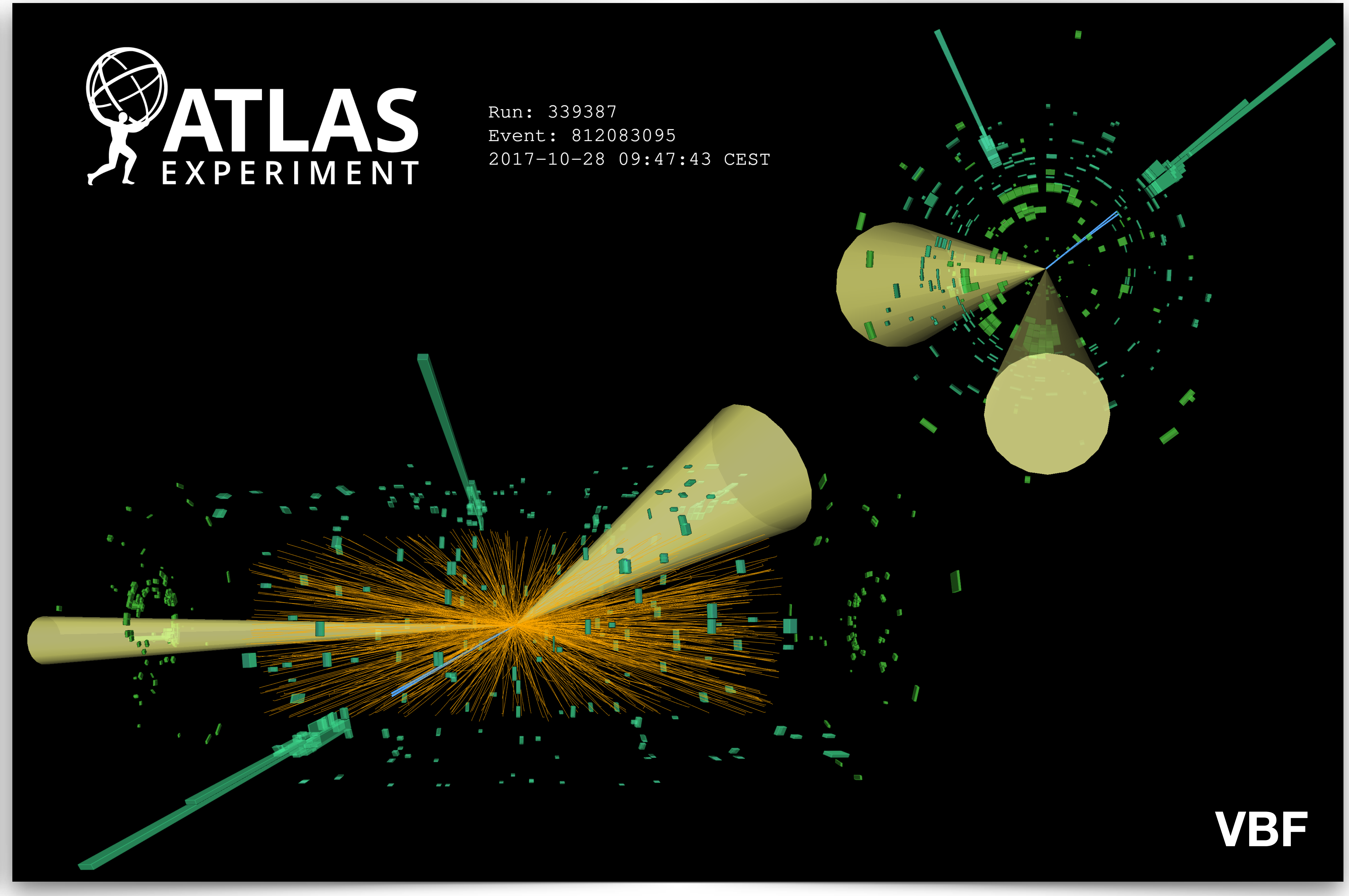
Observed 2.0σ

$$\mu = 1.2 \pm 0.6$$

Result dominated by statistical uncertainty, but watch systematics!

Evidence for $H \to \gamma^* \ell^+ \ell^-$





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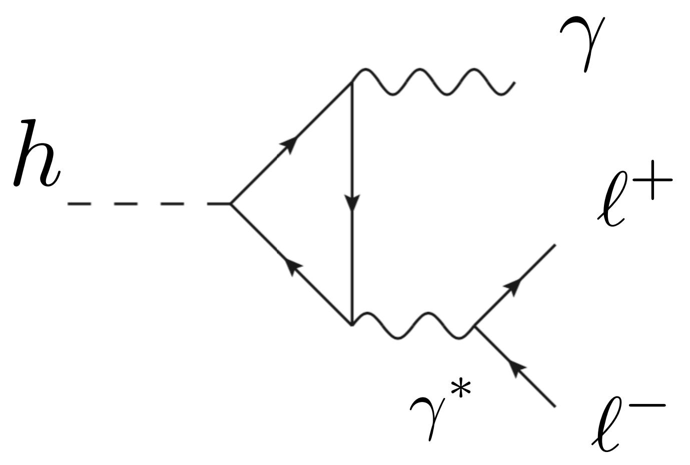


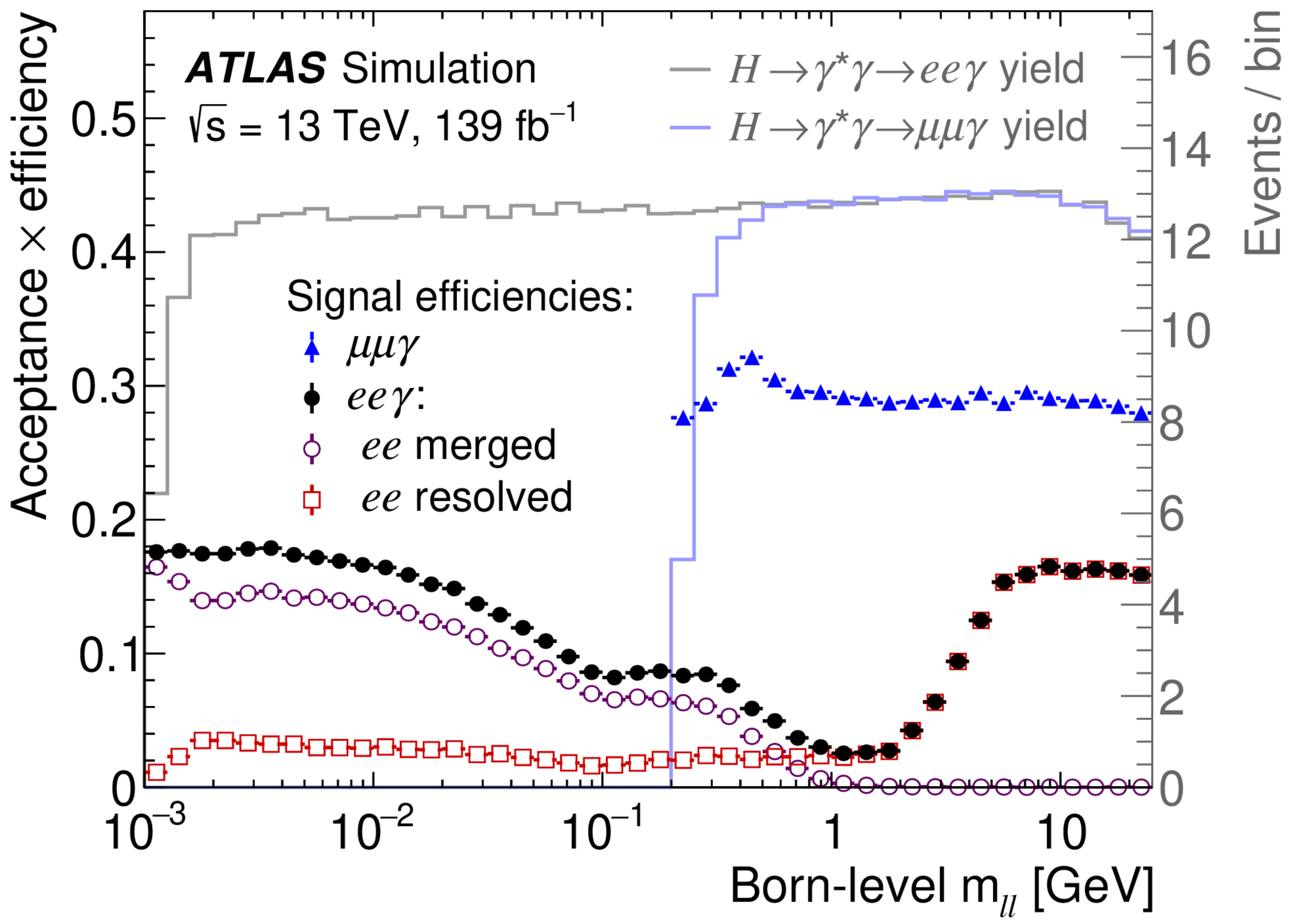
$m_{\ell^+\ell^-} < 50$ GeV

Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

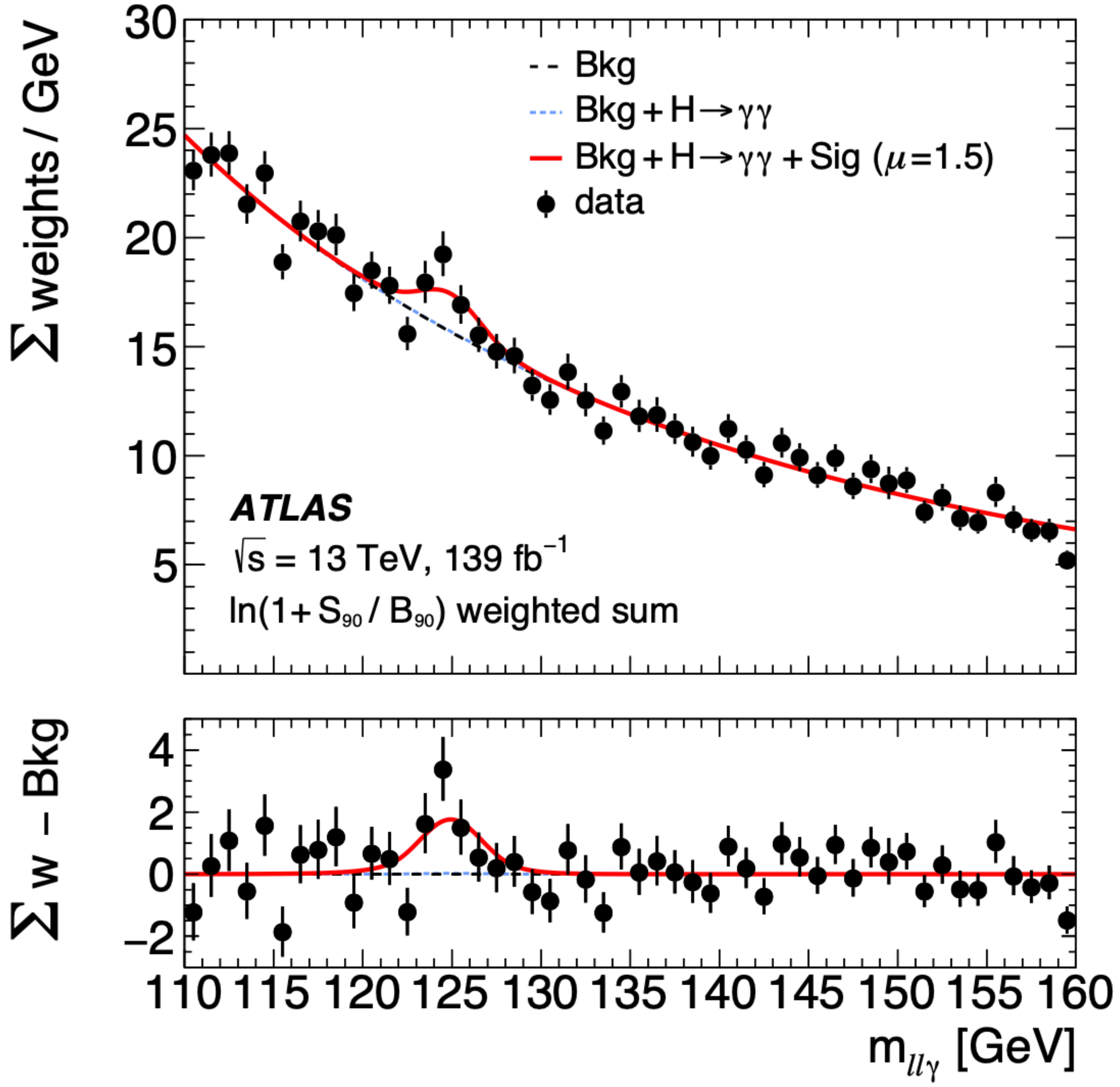
~ 1.7% of $Br(\gamma\gamma)$

Key experimental challenge is to go to low dilepton mass this required a **new reconstruction technique**:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!



Phys. Lett. B 819 (2021) 136412



- 3 x 3 categories (VBF, high pT ggF, low pT ggF) ⊗ (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

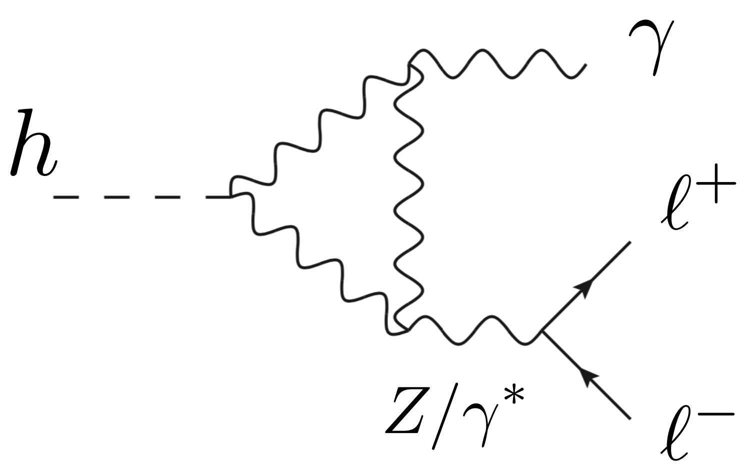
Expected 2.1σ

Observed 3.2σ

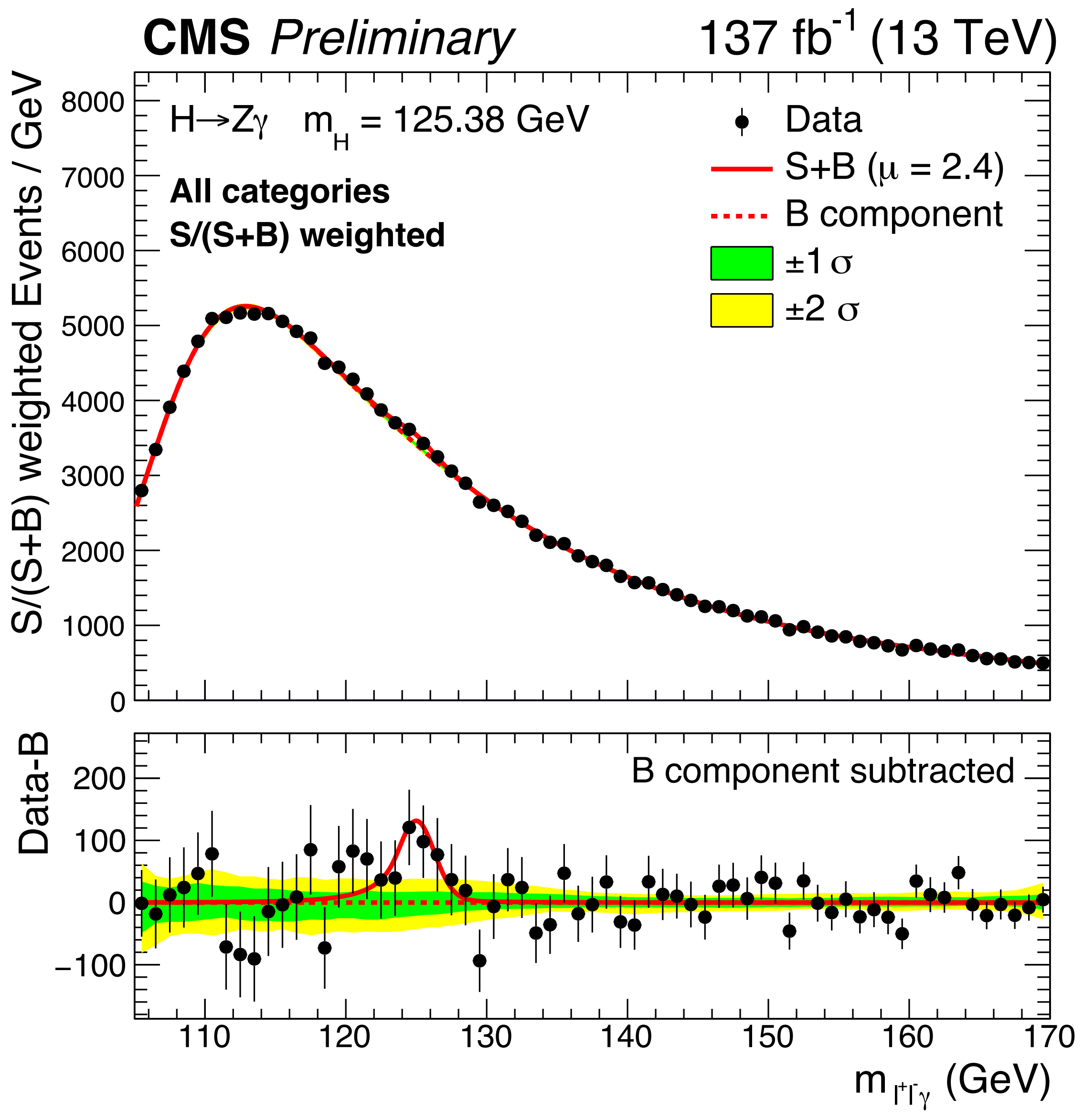
Searches for the $H \to Z\gamma$ Decay Mode

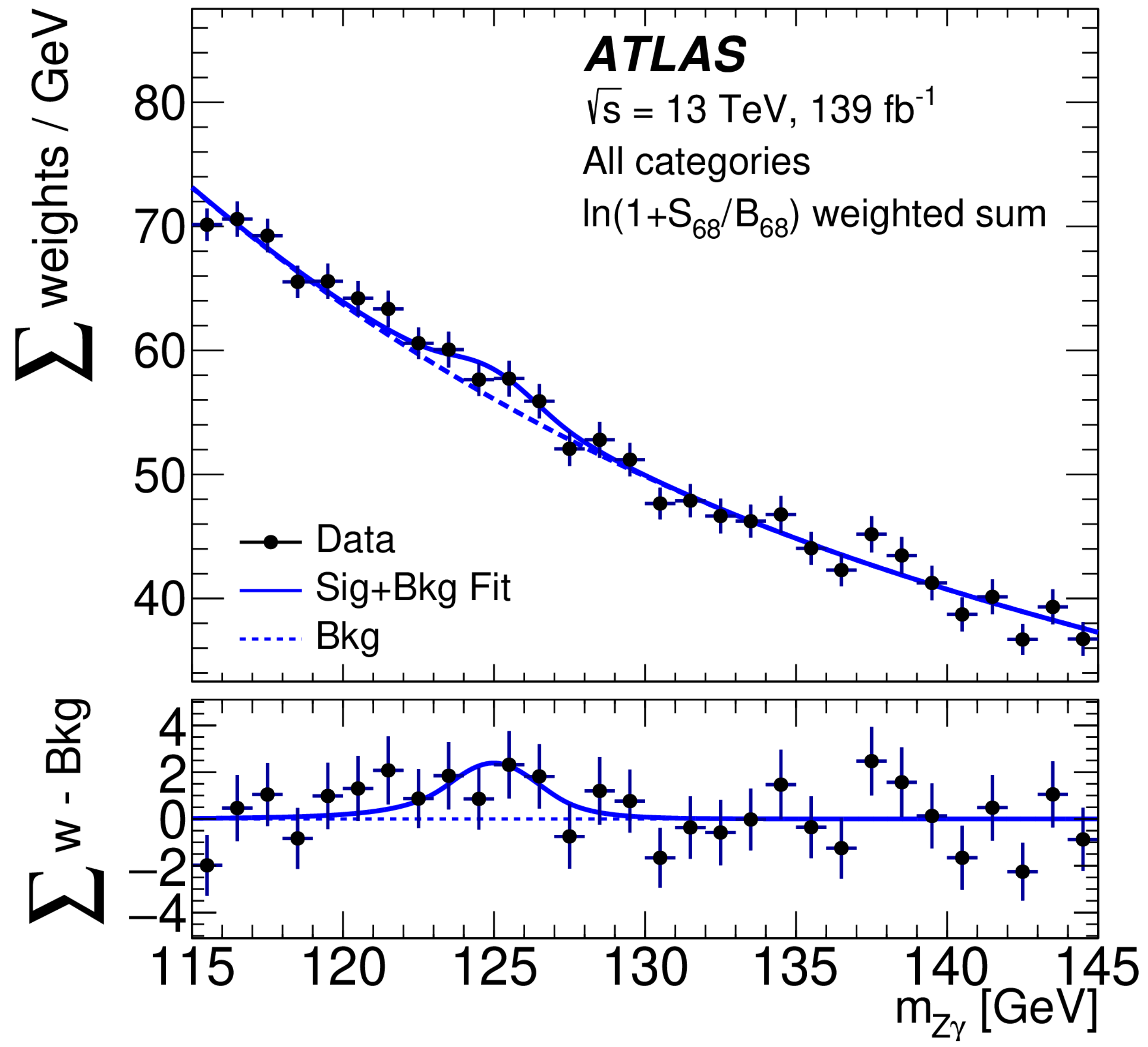
Z-photon $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$

Field tensor coupling not measured yet!

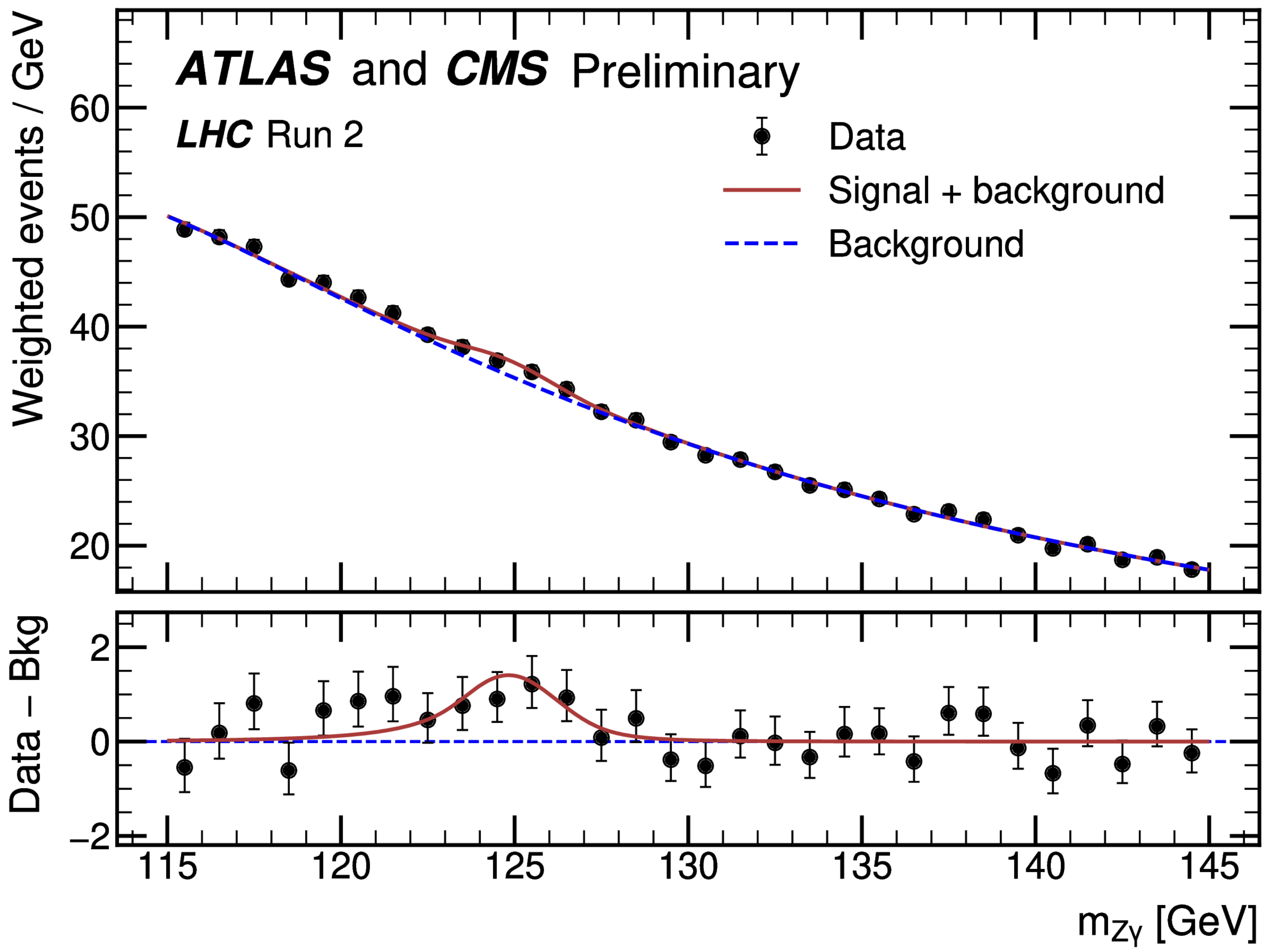


~ 2.3% of $Br(\gamma\gamma)$





Combined ATLAS and CMS mass spectrum!



CMS Result

ggF, VBF, VH and ttH enriched

Expected 1.2σ

Observed 2.7σ

ATLAS Result

ggF and VBF enriched

Expected 1.2σ

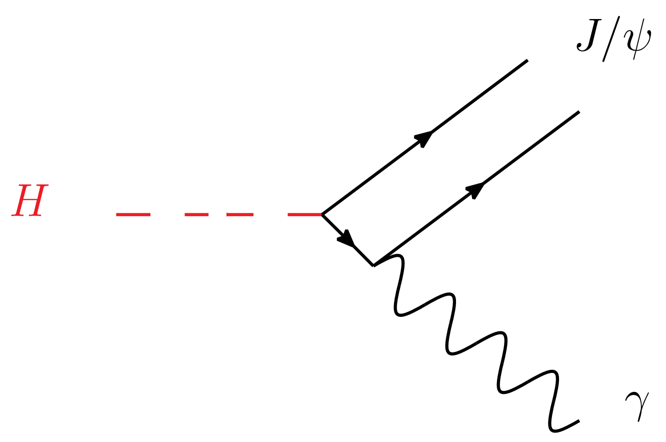
Observed 2.2σ

Combined search yields 3.4σ observed and 1.6σ expected (consistent with the SM expectation at the 1.9σ): First evidence!

HL-LHC **~10%**

More Rare Decays and Production

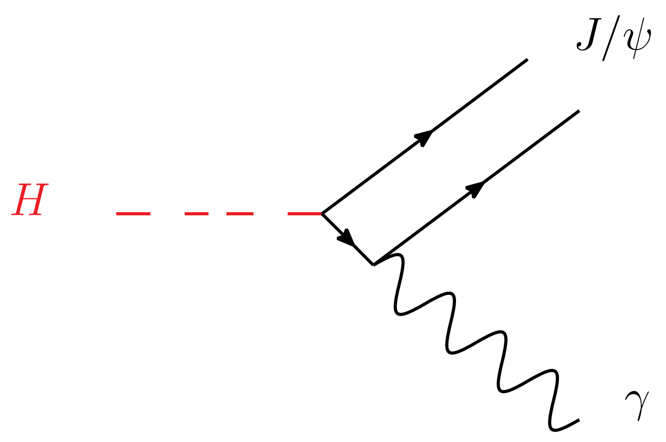
Quarkonia-photon



Potentially sensitive to charm Yukawa

$\mu^+\mu^-\gamma$

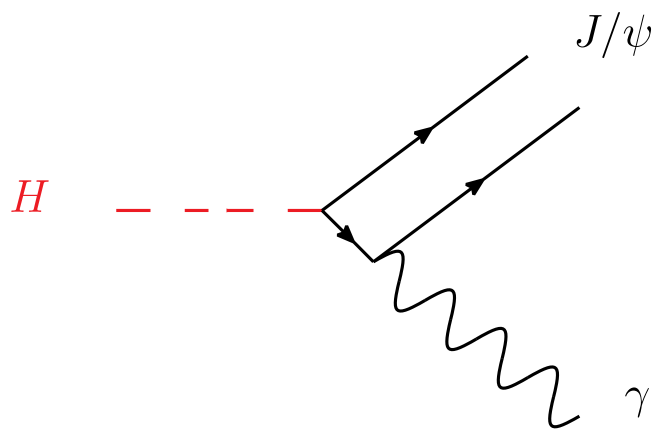
~100 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

~200 x SM

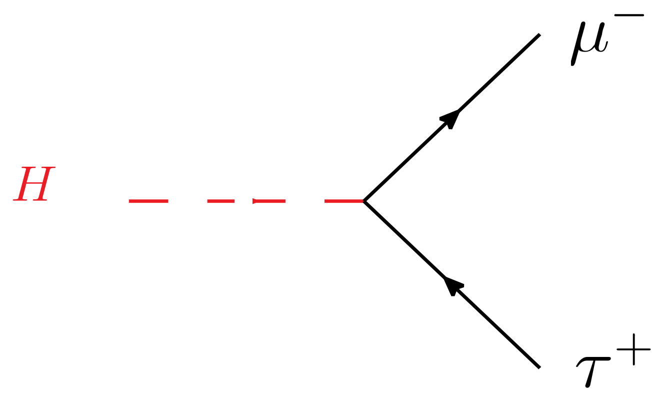


Potentially sensitive to light Yukawa

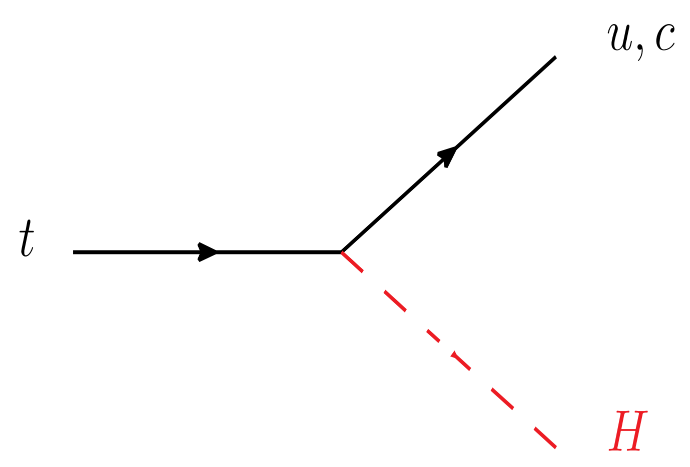
$\pi^+\pi^-\gamma$

~50 x SM

Lepton flavor violating decays

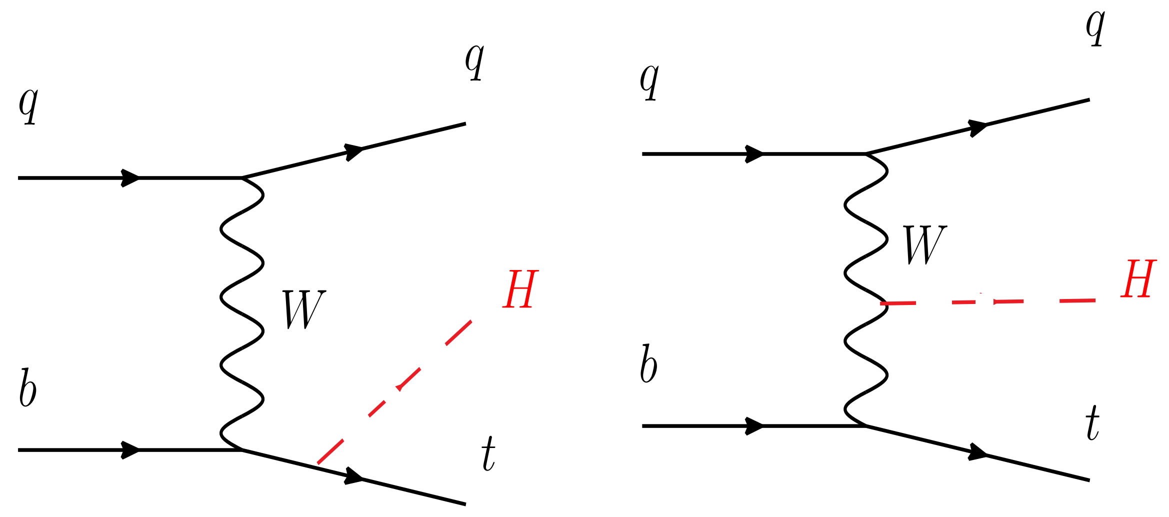


FCNC decays of the top quark



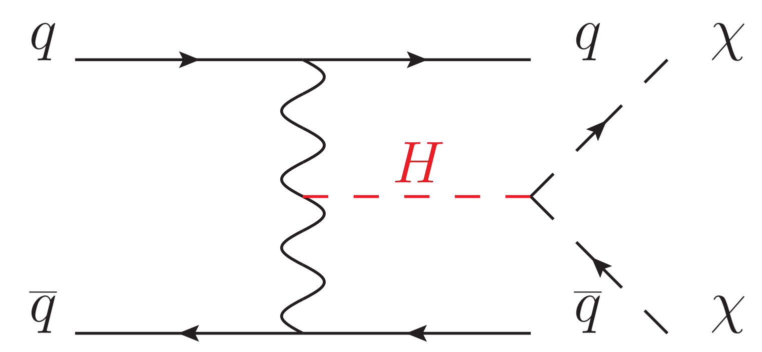
Various decay channels of the Higgs boson (diphoton, bb)

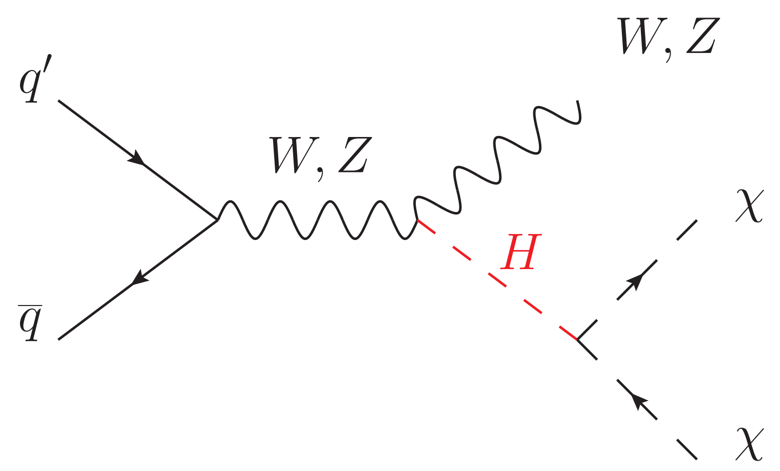
Single top associated production

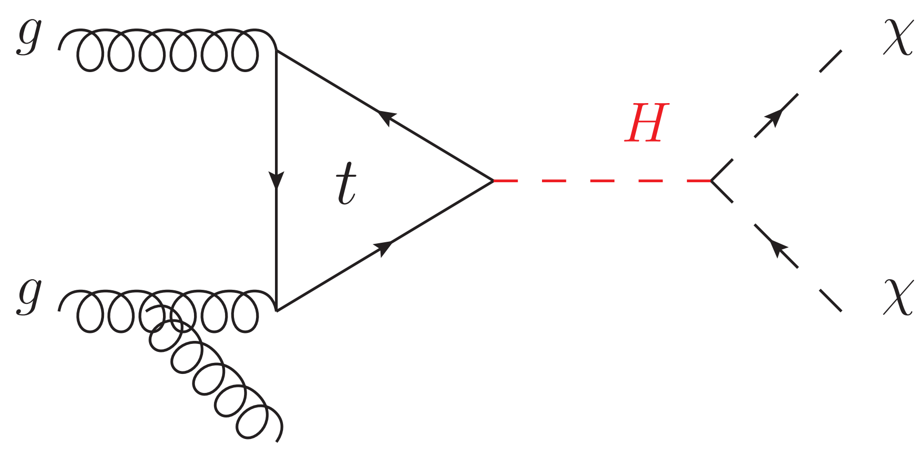


Tree level interference between W and top

Invisible decays





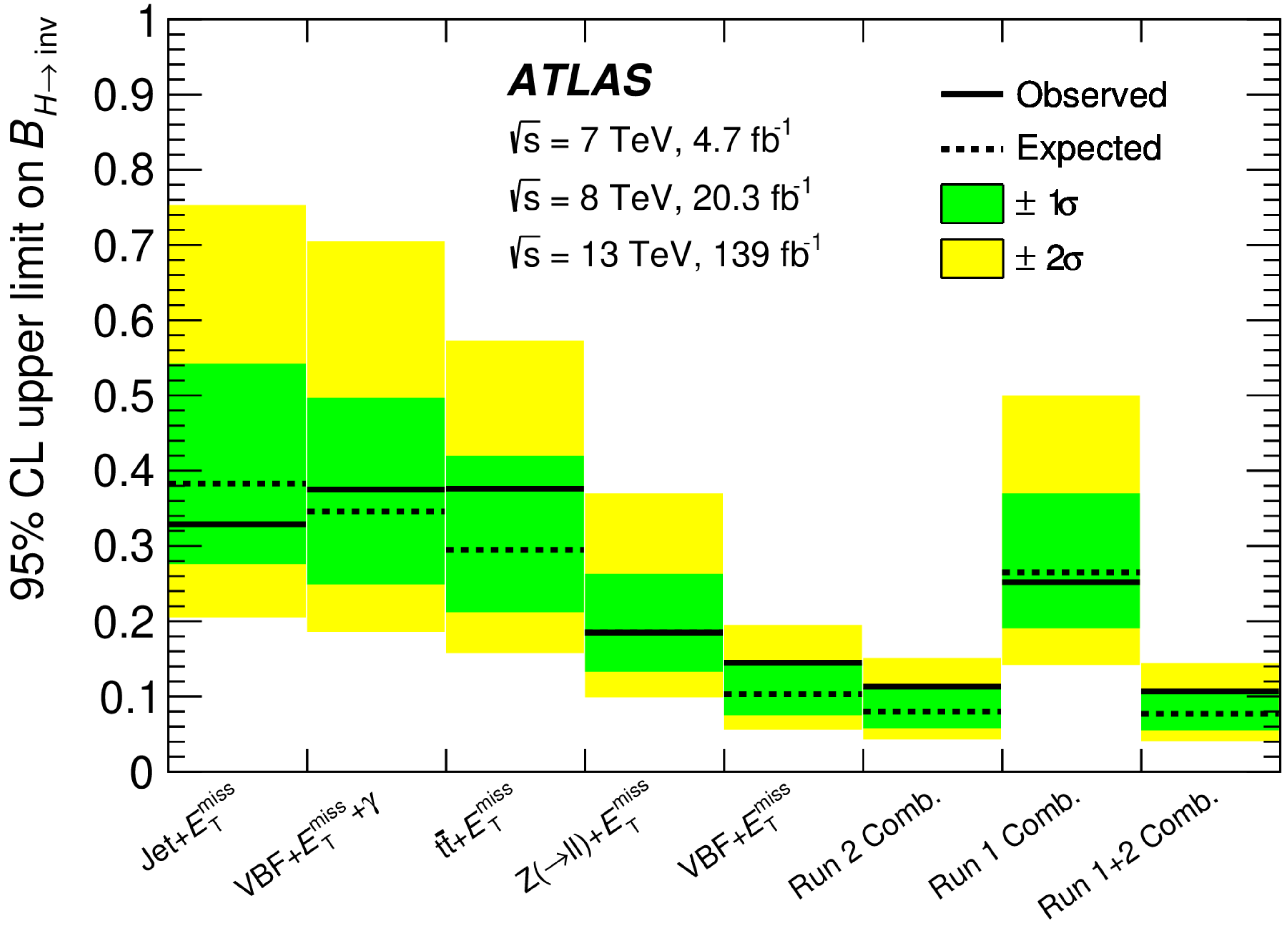


<11% @ 95% CL

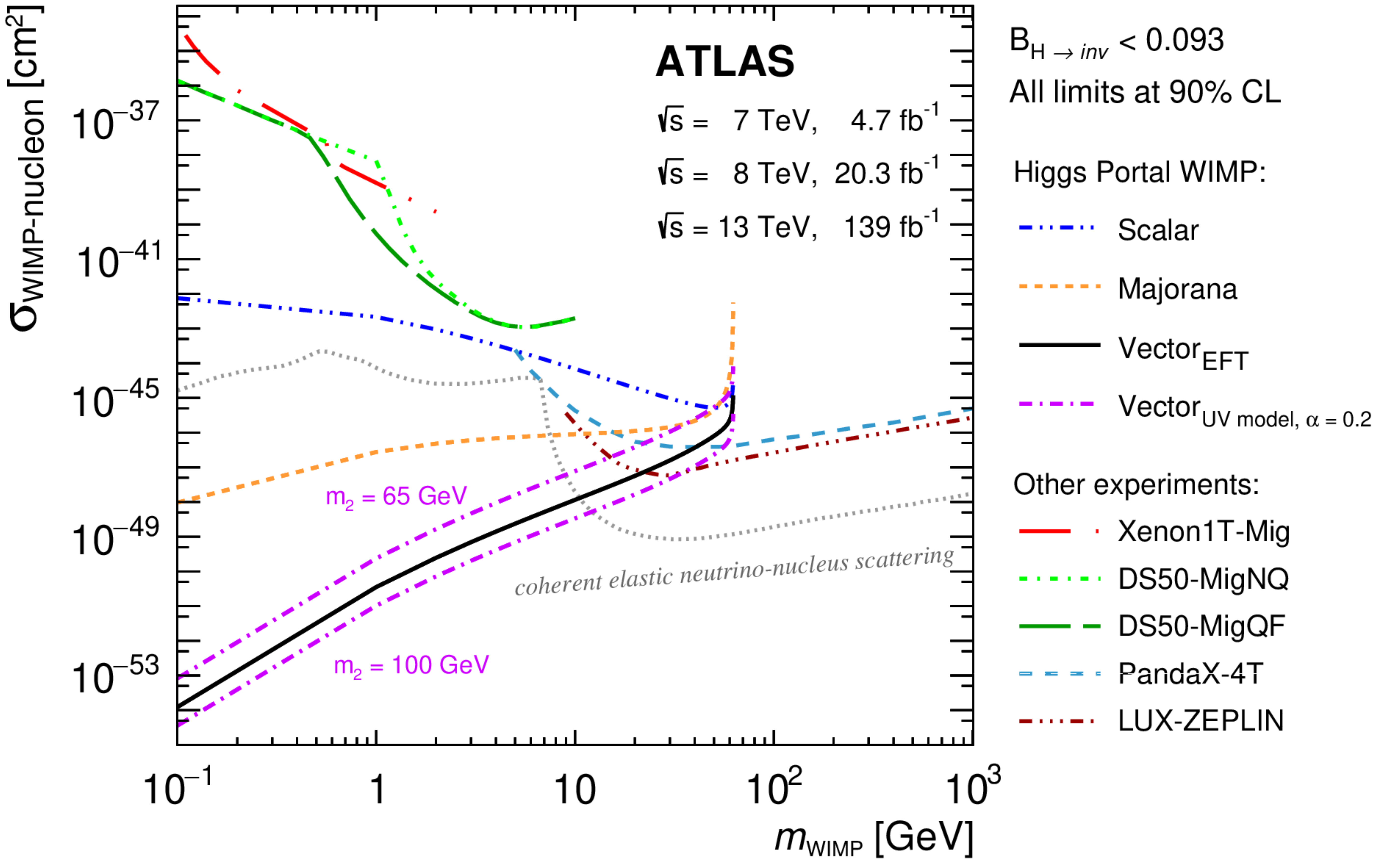
HL-LHC 2.5%

Invisible Higgs Decays

To be precise: upper limit on the H→invisible branching of **0.107** (0.077) at the 95% CL

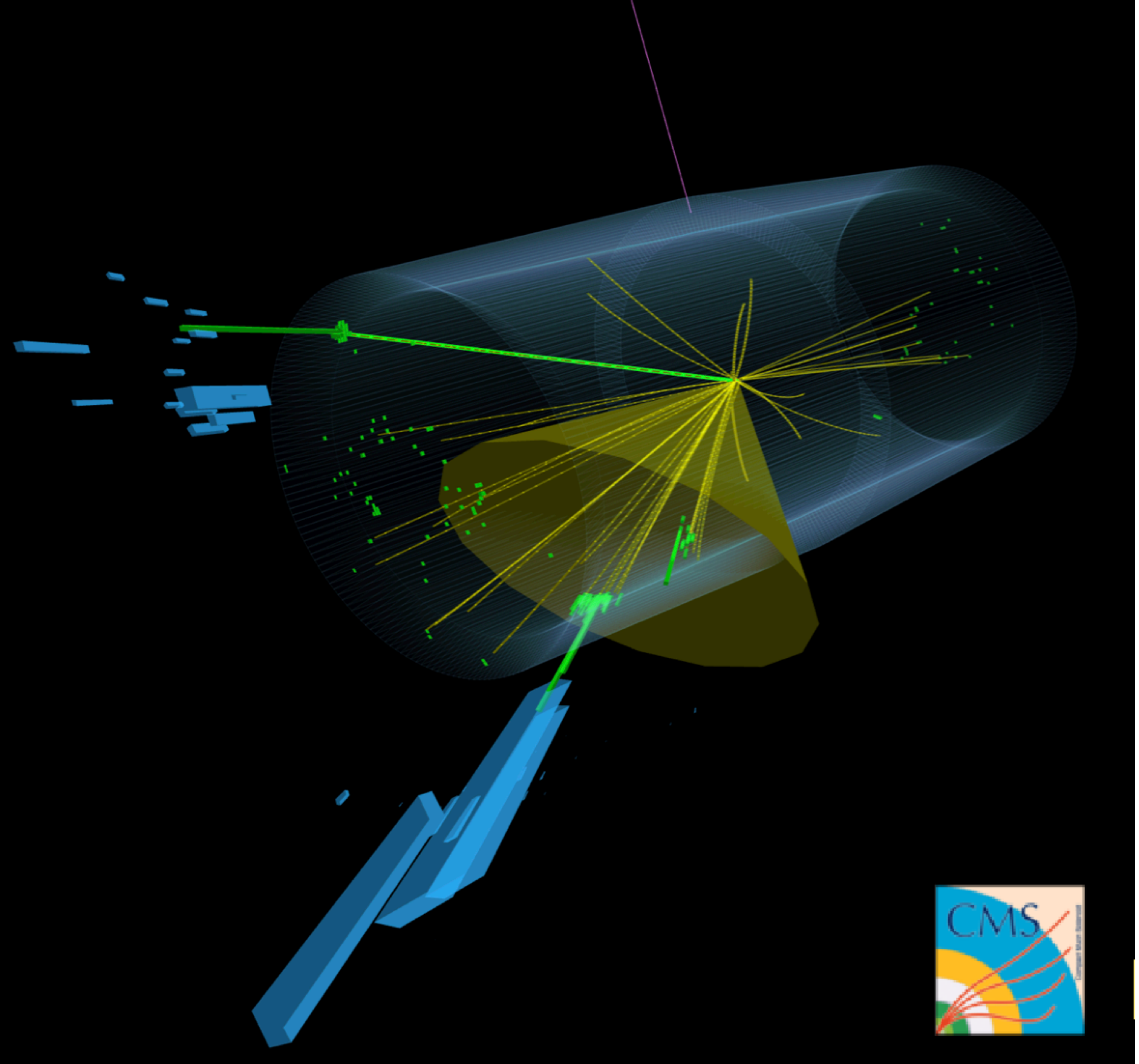


In the SM the H→invisible branching of **0.1%**



Should reach 2% level at HL-LHC! Major milestone for Run 3

The Yukawa coupling to charm



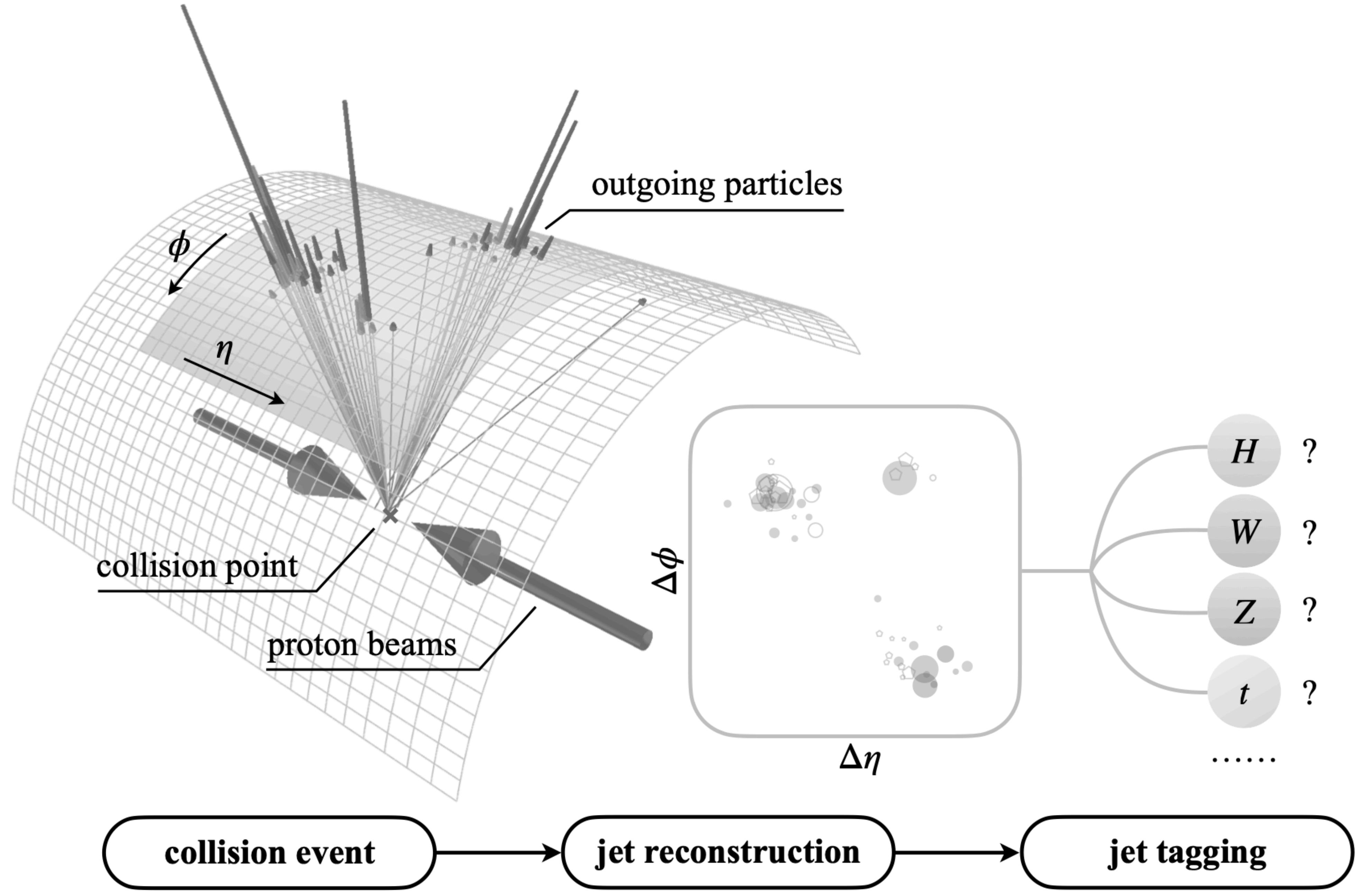


Illustration from Particle Transformer

Use of state-of-the-art ML techniques

Use "particle clouds" (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

Particle Net uses Dynamic Graph CNN

The challenging Yukawa coupling to charm

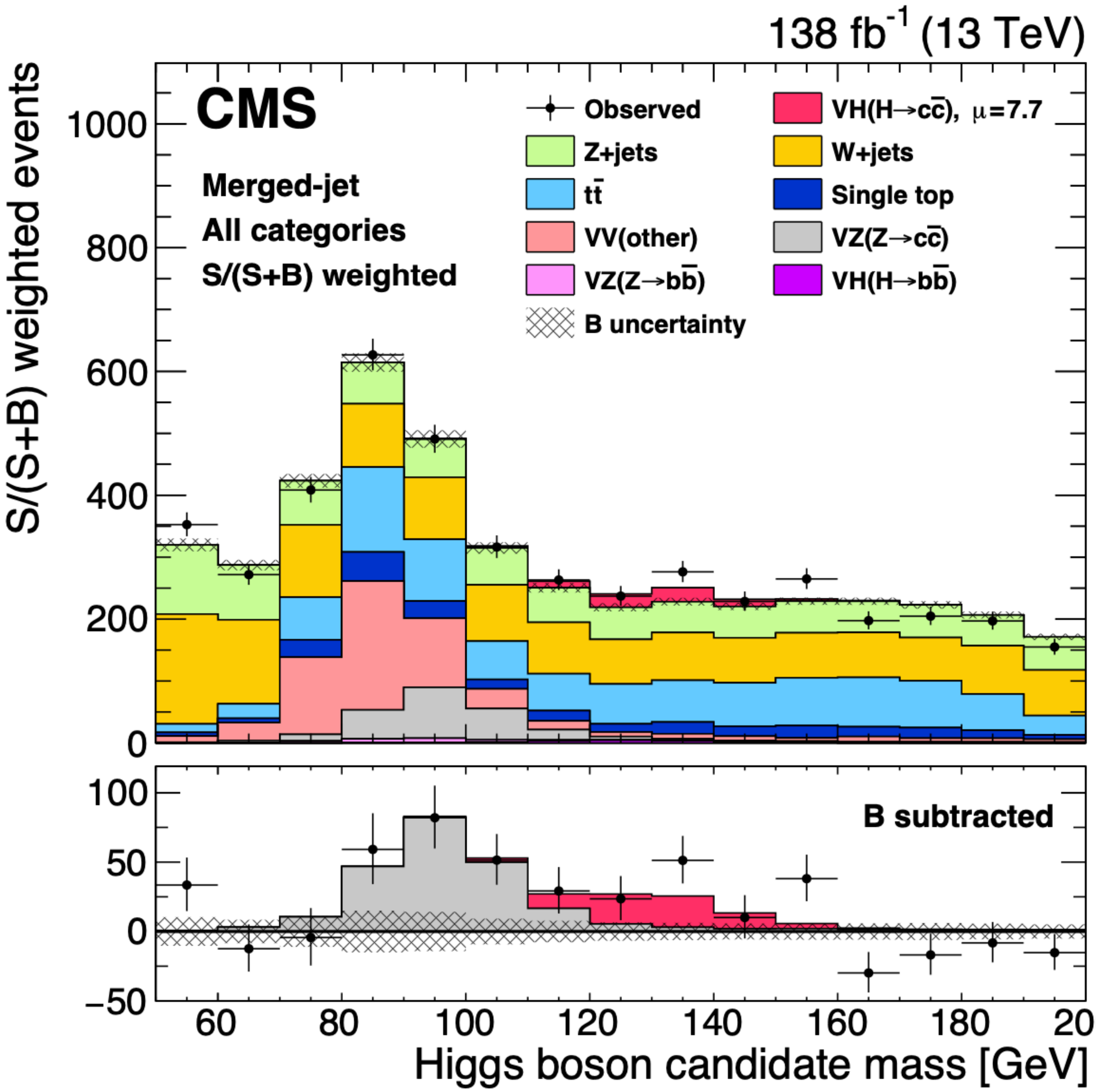
Signal normalisation:
μ < 14.4

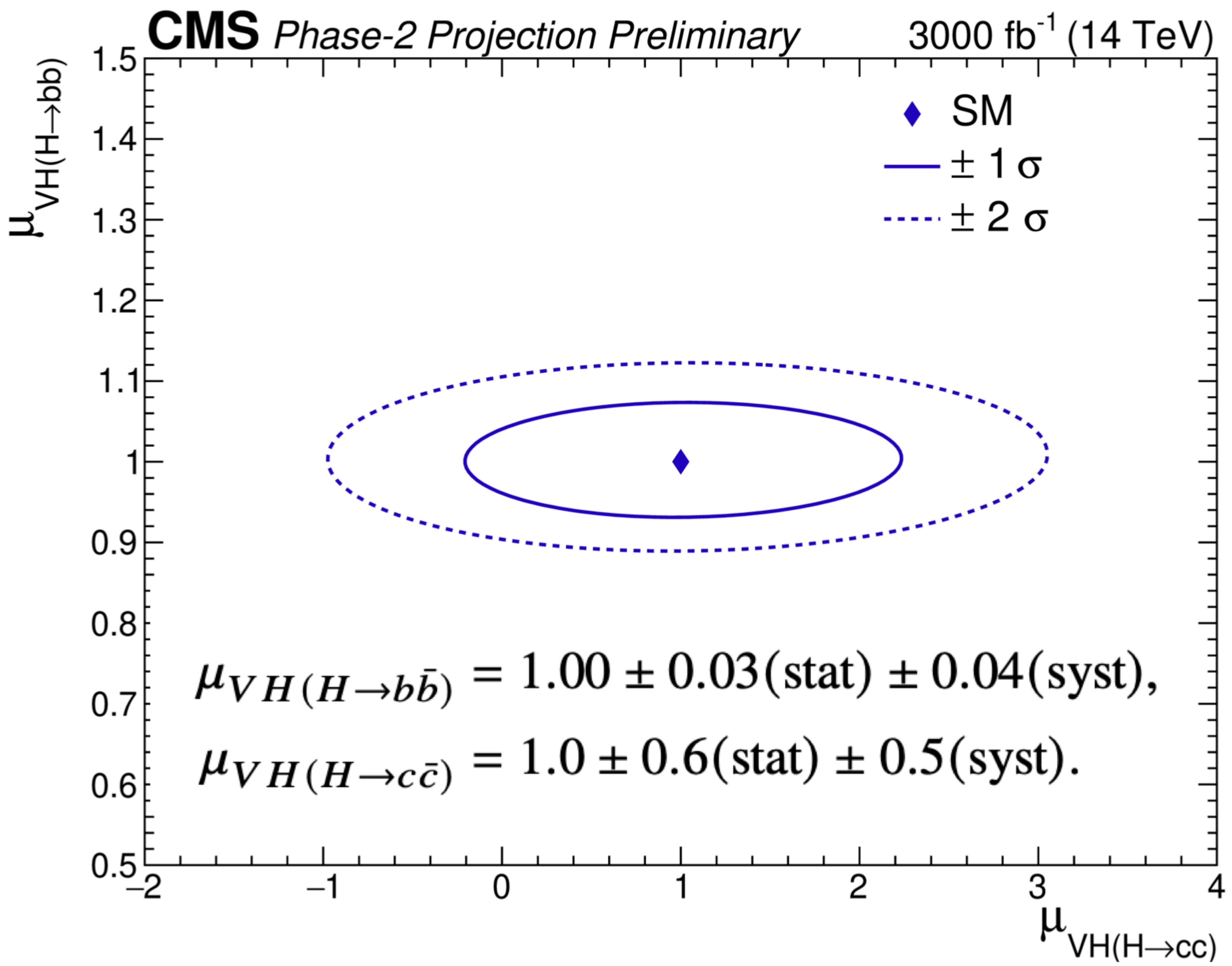
Impact of boosted

Resolved: 19.0 (exp)
Boosted: 8.8 (exp)
Combined: 7.6 (exp)

Constraints on charm Yukawa

$1.1 < \kappa_c < 5.5$



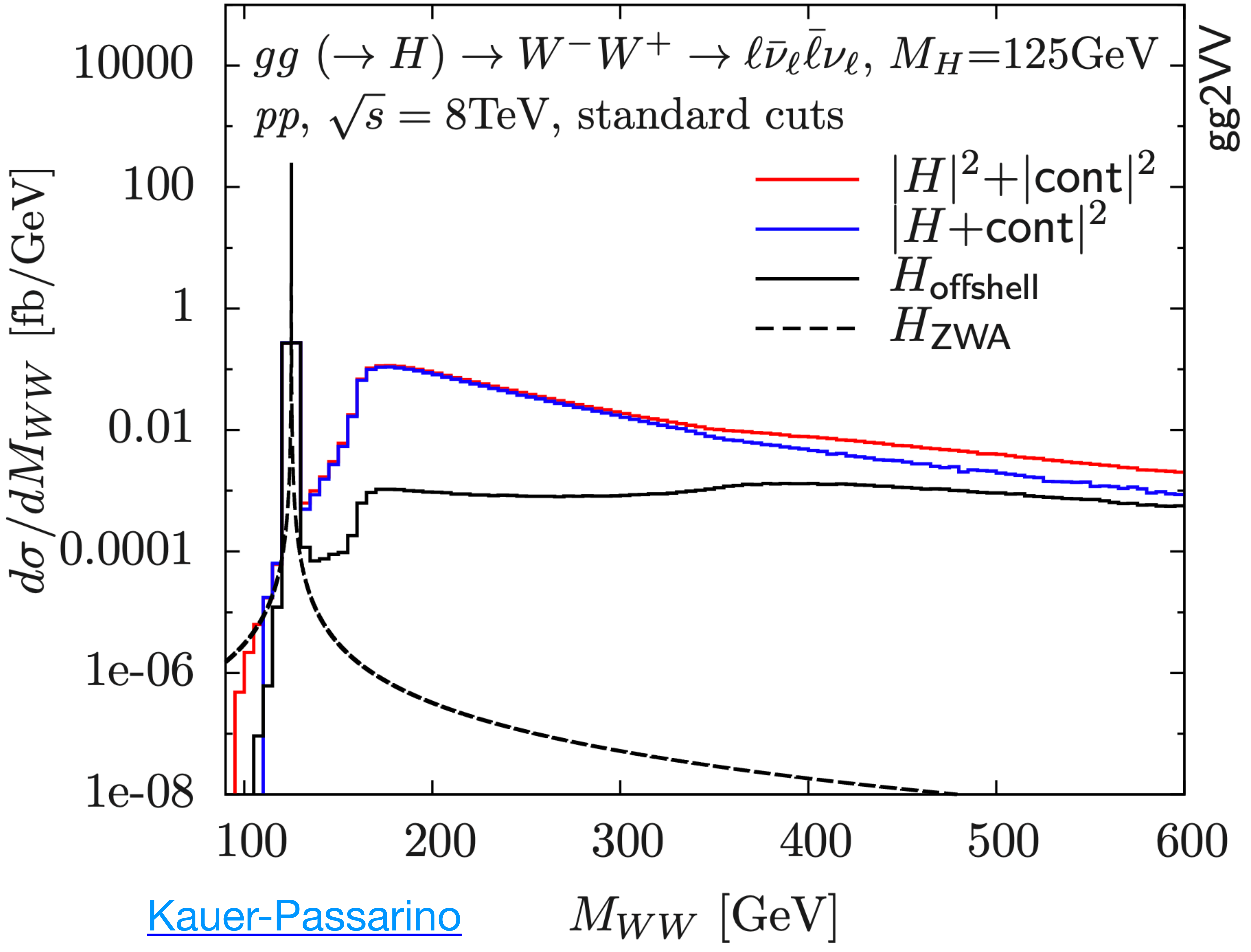


Yields a precision on κ_c of ~40% per experiment

This result is very encouraging on the possibility of being sensitivity to this process at the LHC

Off Shell HVV Couplings and Width

Off Shell couplings



Kauer-Passarino

Higgs Boson width

Assumption of Standard Model and comparison to on shell allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2\kappa_V^2)_{on\ shell} = (\kappa_t^2\kappa_V^2)_{off\ shell}$$

Current measurement (CMS) PRD 99 (2019):

$$\boxed{\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}}$$

Evidence for Off-Shell production at 3.6σ

at HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Remarkable result to follow closely at Run 3!
How much better can be done at HL-LHC?

The Higgs Self Coupling An Outstanding Goal for HL-LHC and Beyond

Di-Higgs Production

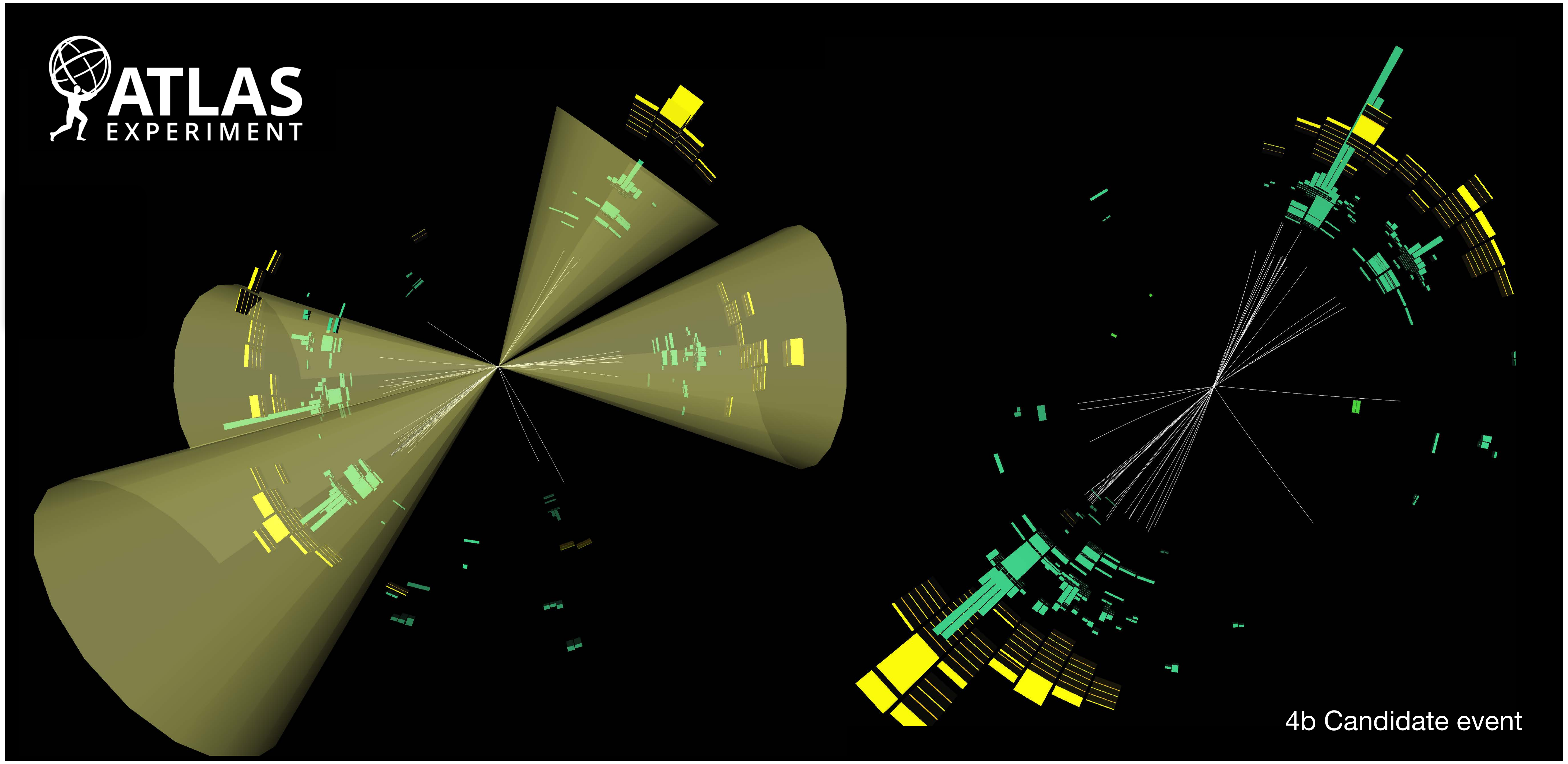
Measuring the di-Higgs production provides a unique and direct probe of the Higgs boson self-coupling

Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production!

Huge challenge! but still more than 100k event will be produced at HL-LHC!

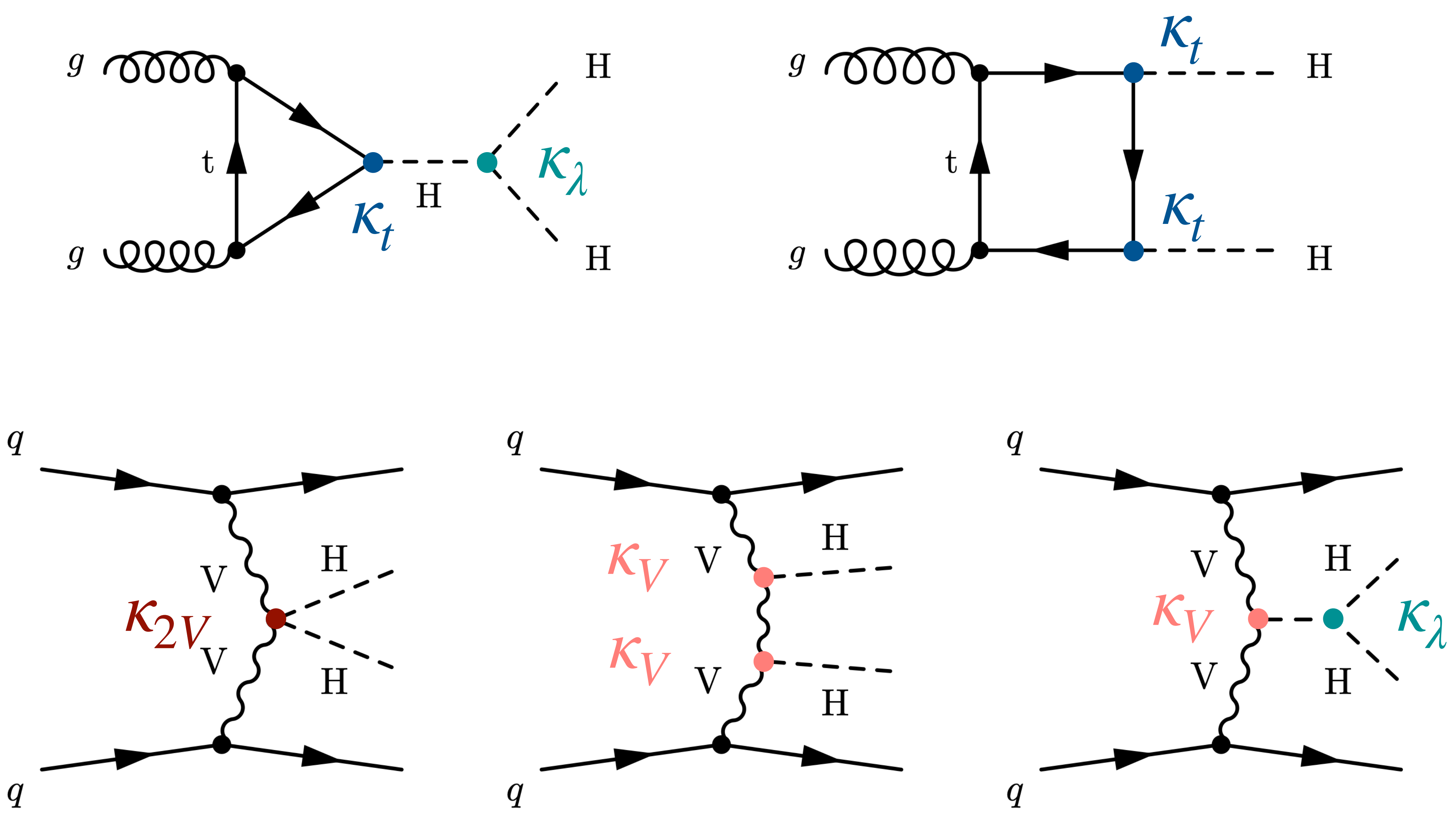
Fairly complex signatures (not outrageously so!)



Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

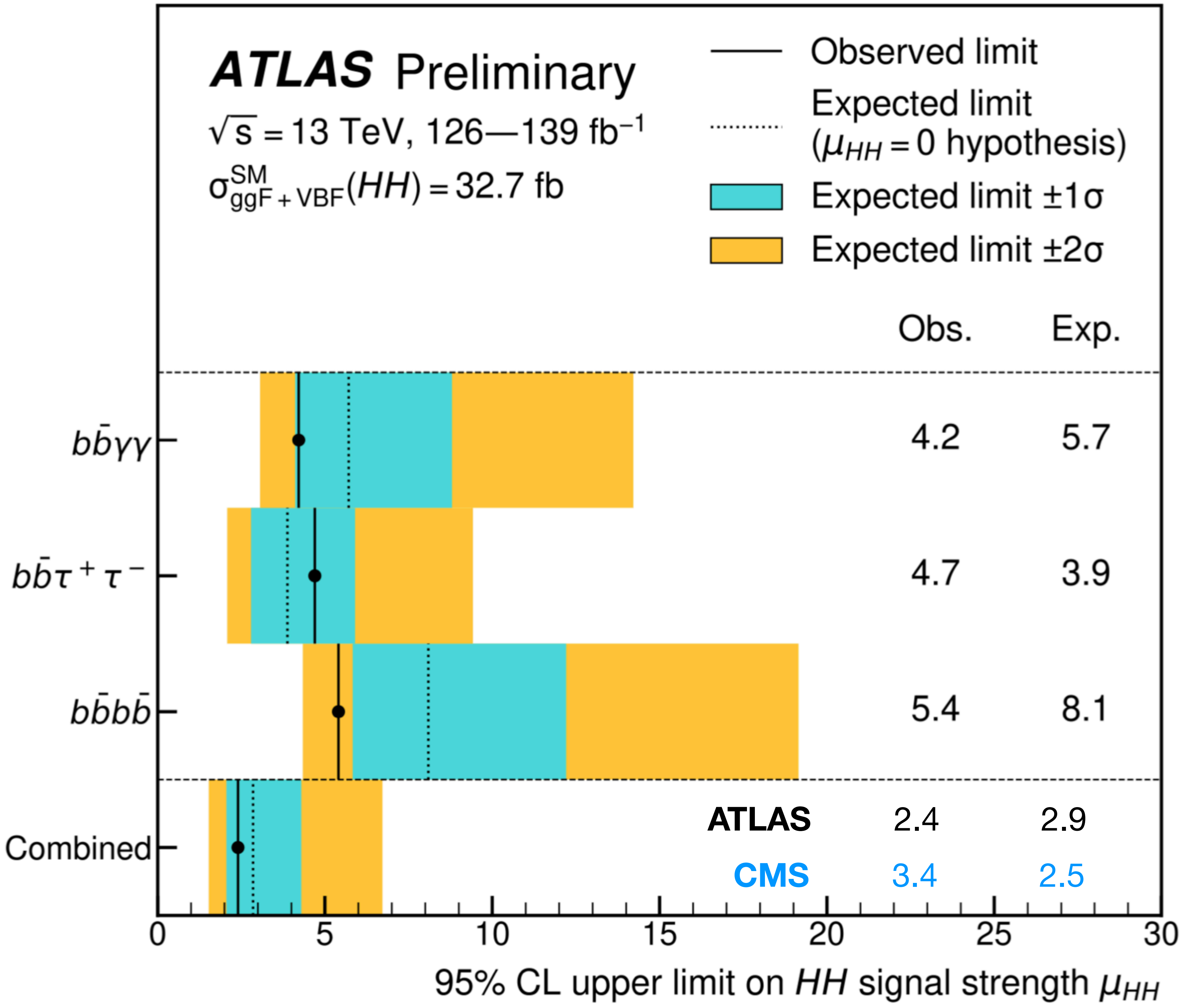
HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (VH and VBF)



With the VBF production mode not only limits on κ_λ also on κ_{2V}

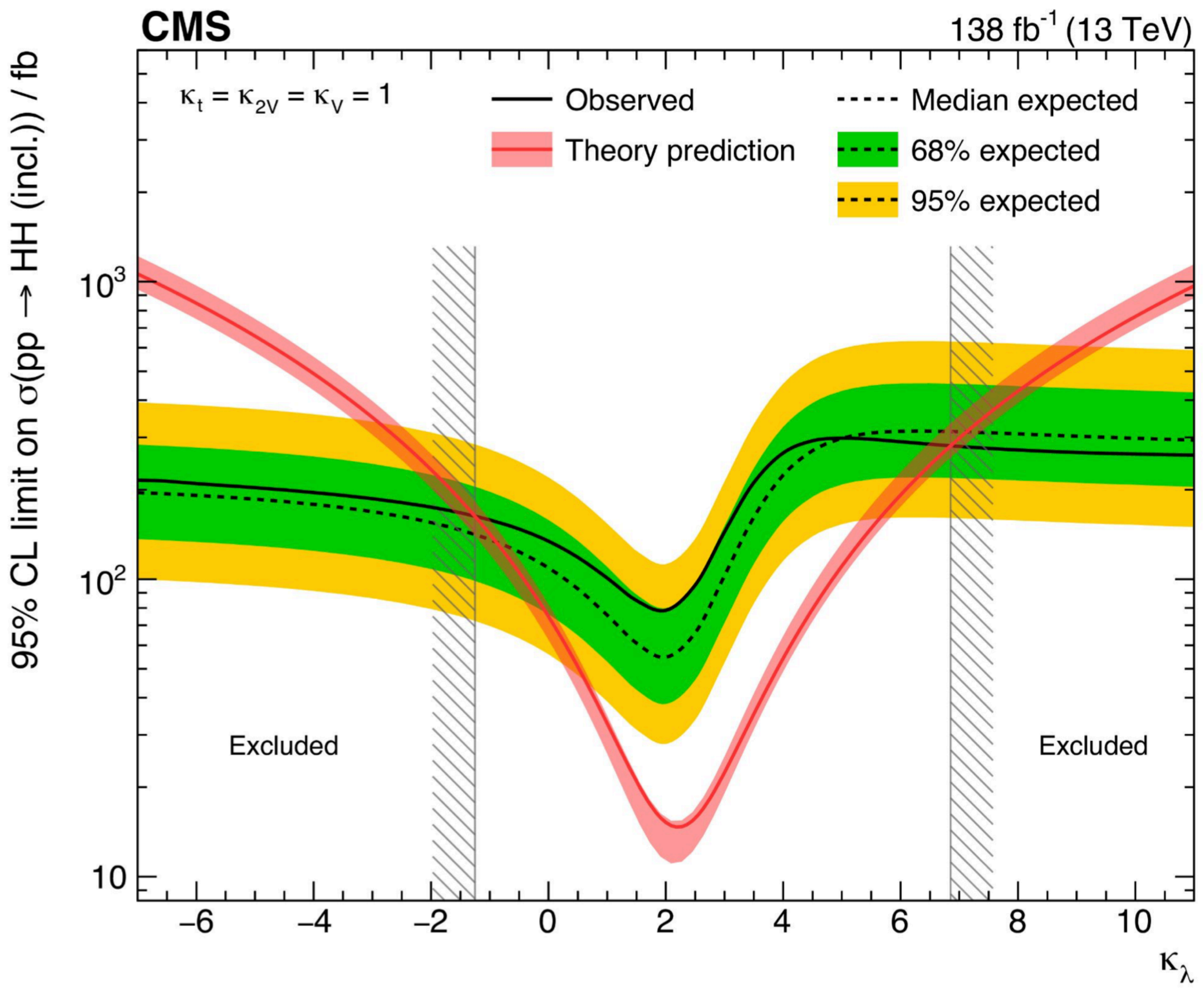
Bishara, Contino, Rojo



More than 3 times better limits than with 36 1/fb!!

HH Production and Higgs Self coupling

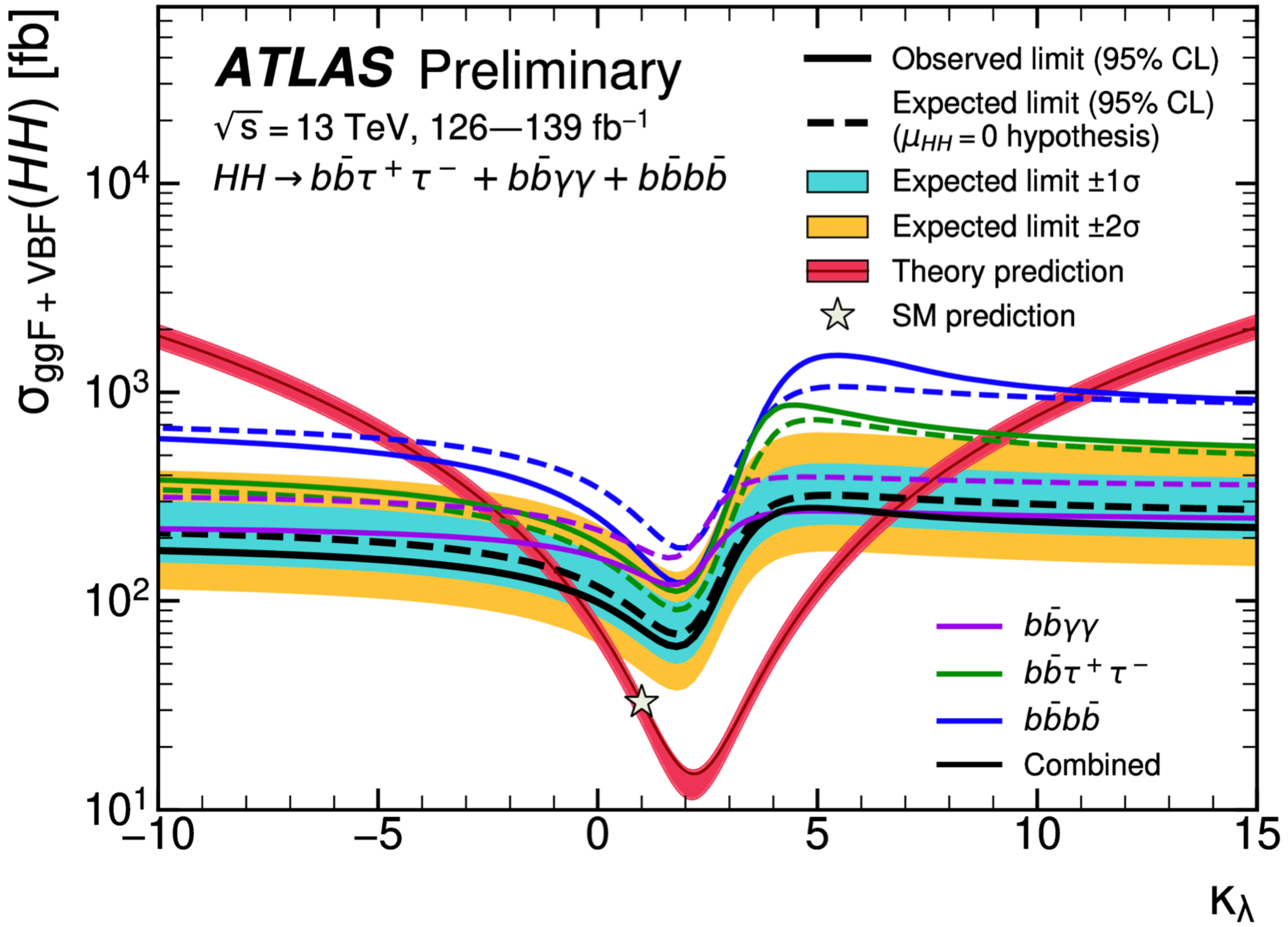
Partial combination in CMS



CMS $-1.24 < \kappa_\lambda < 6.49$

Expected interval similar

Partial combination in ATLAS



ATLAS

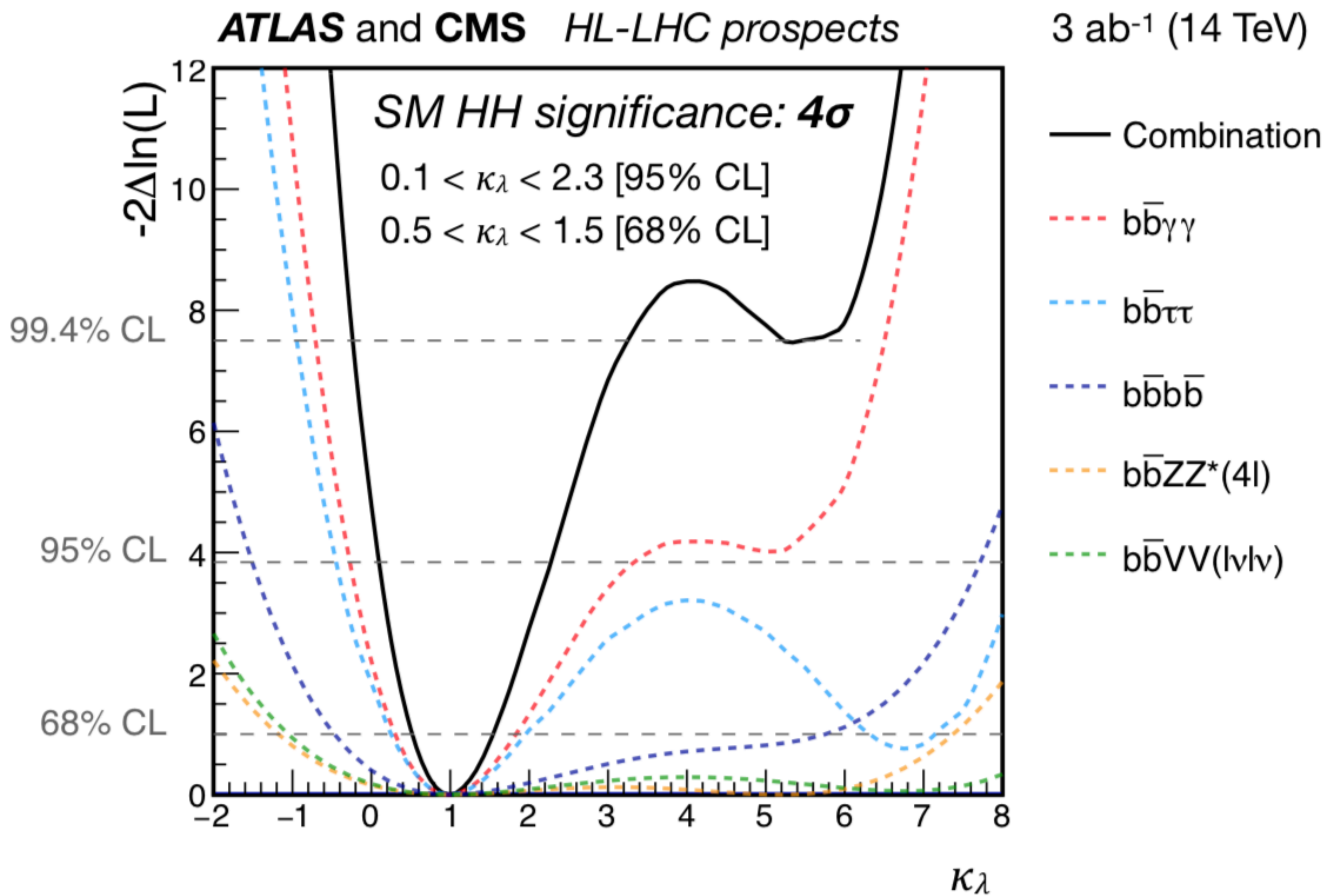
Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

HH Production and Higgs Self coupling

From P. Huang, A. Long and L.-T. Wang

At HL-LHC



Current estimates yield an observation of an HH signal at 5σ

50% level constraints on the Higgs boson self coupling!

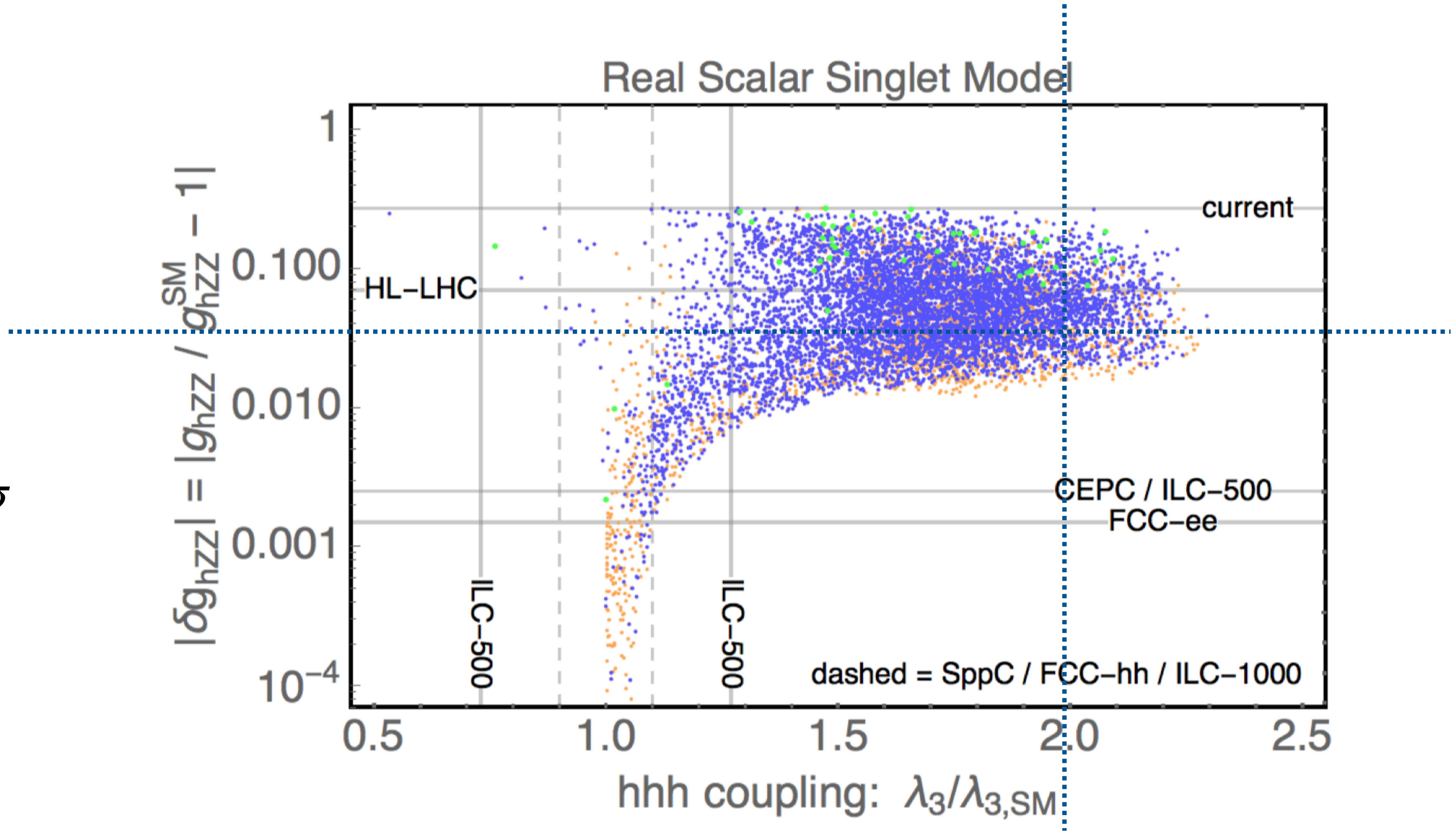
$$0.5 < \kappa_\lambda < 1.5$$

Already impressive, must try all we can to improve!!

Probing 1st order phase transition and GW signals

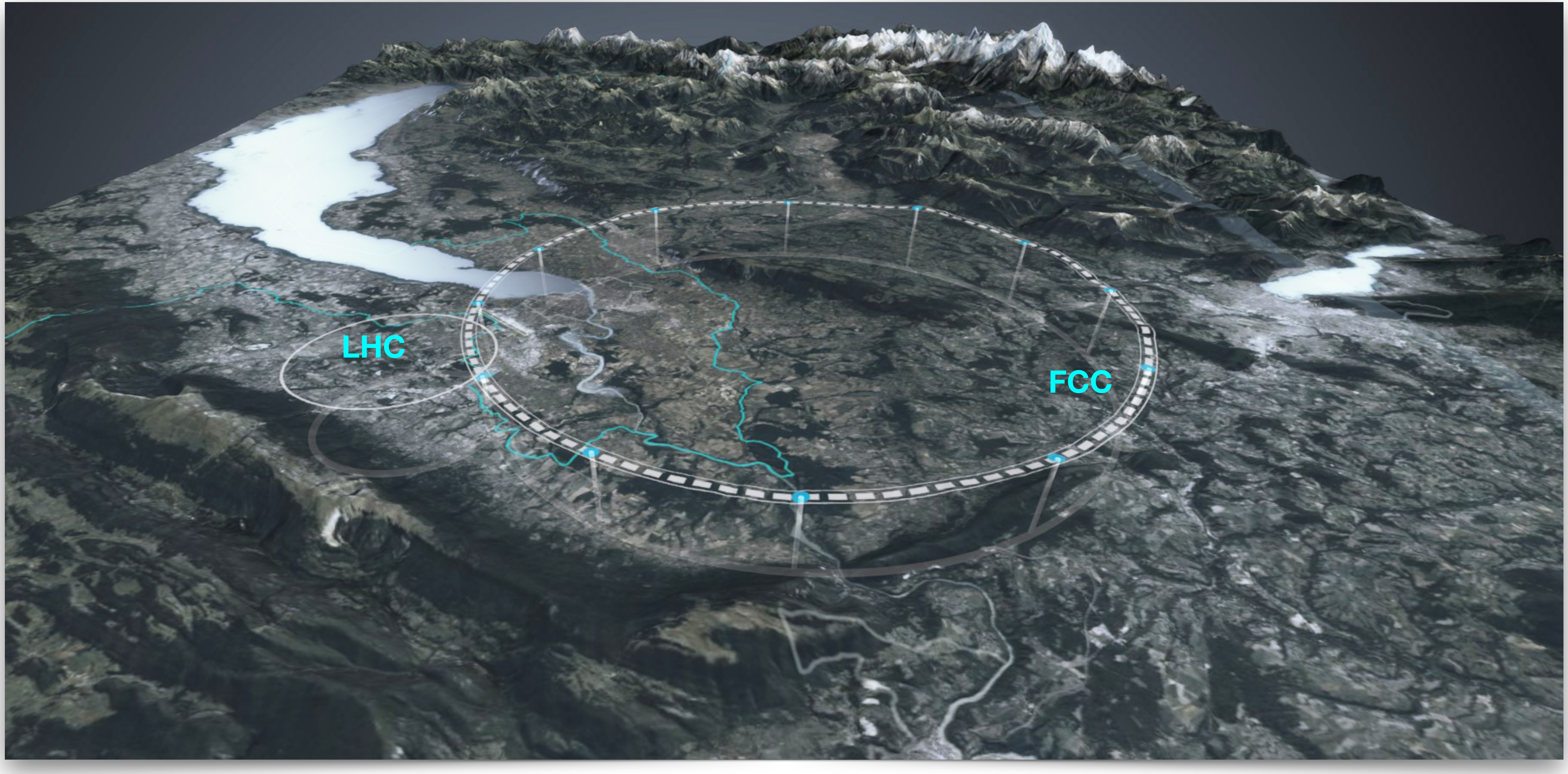
The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

In these cases, signals of stochastic background (e.g. collisions of bubbles) in the phase transition could potentially be detected by next generation interferometers like eLISA*)



*eLISA: evolved LISA

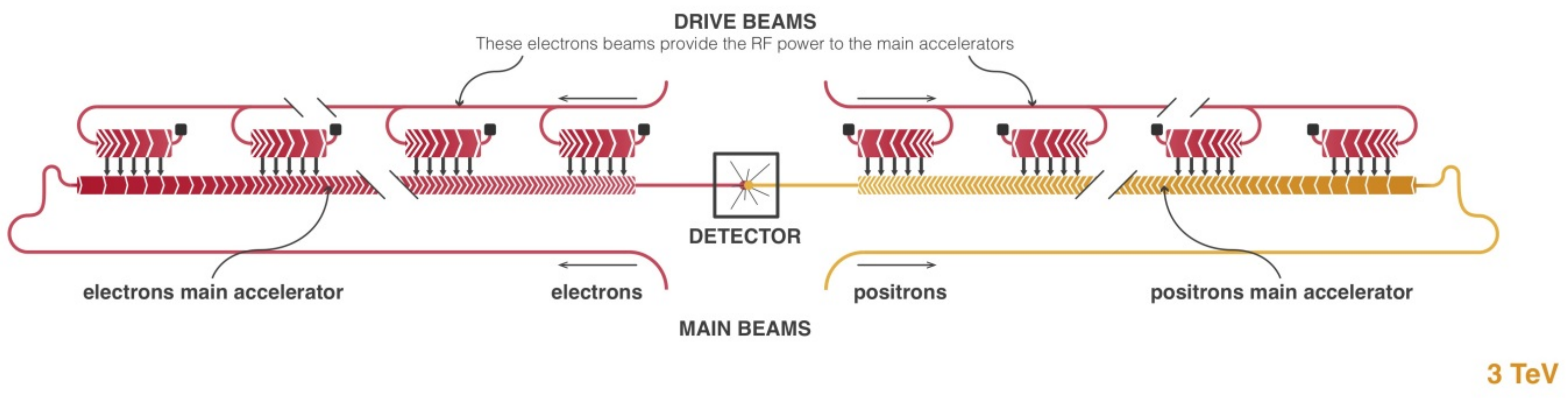
Future Collider Projects



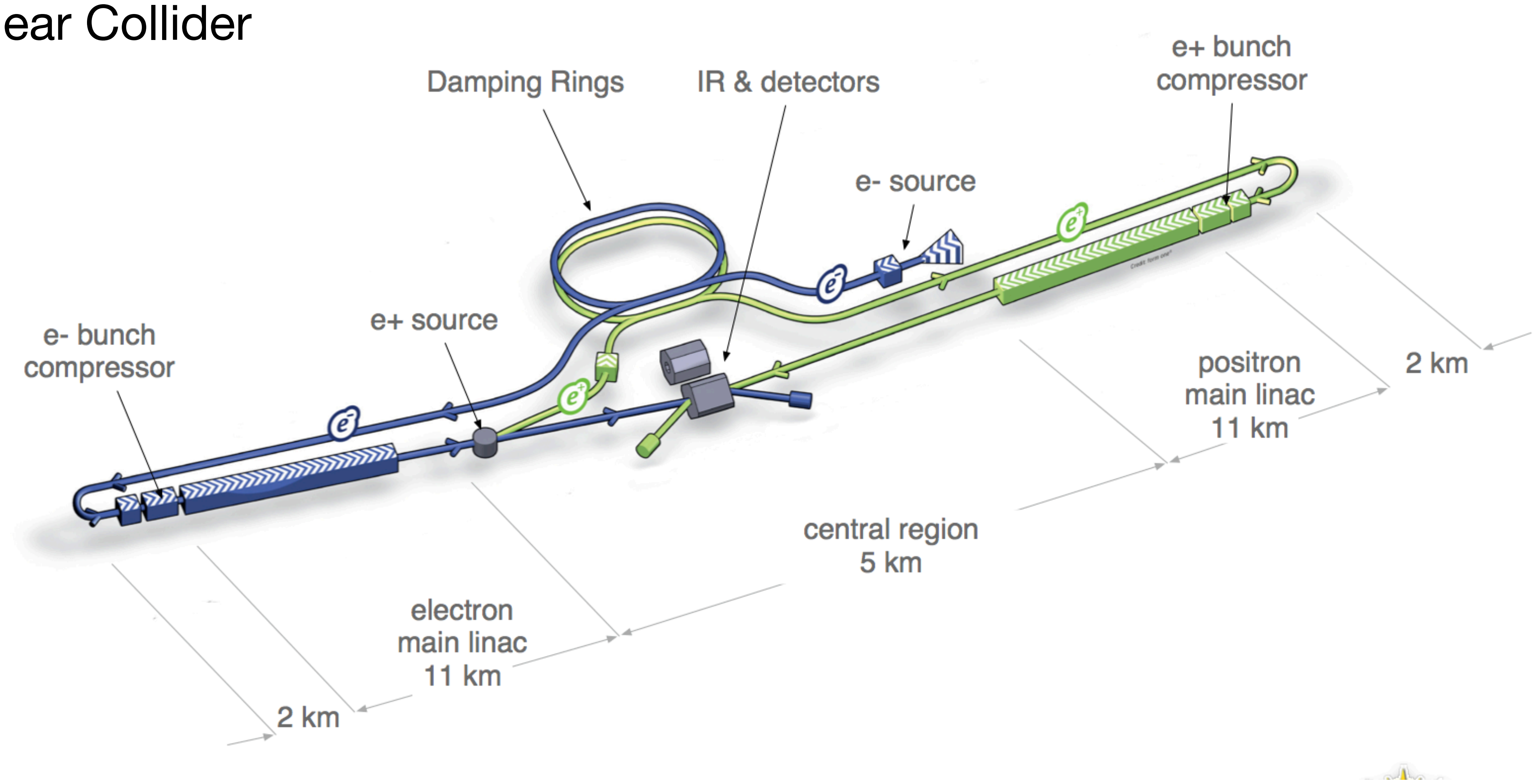
e^+e^- Collider Projects - Linear

Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} cm^{-2}s^{-1})	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

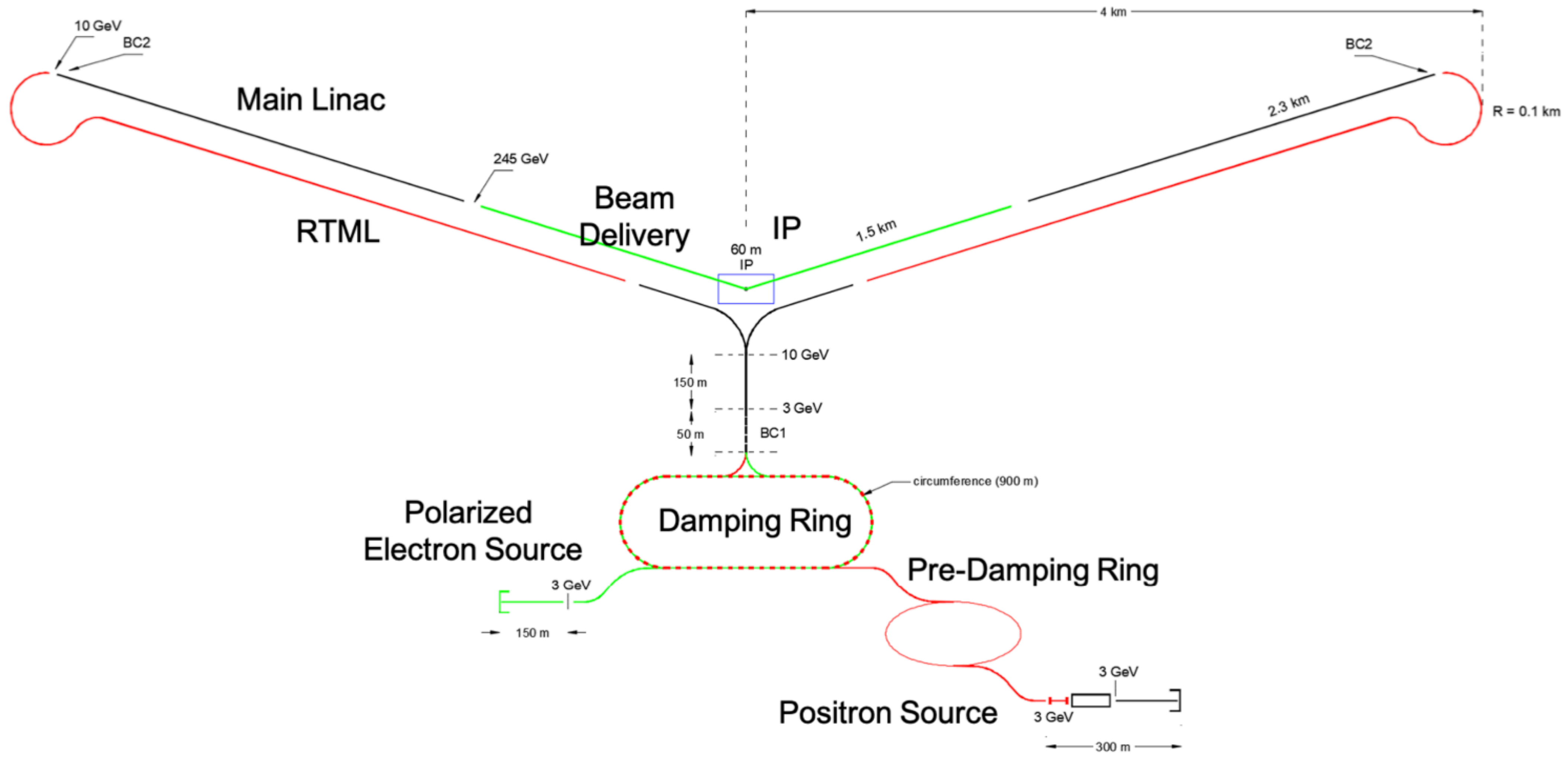
CLIC Compact Linear Collider



ILC International Linear Collider



C^3 Cool Copper Collider

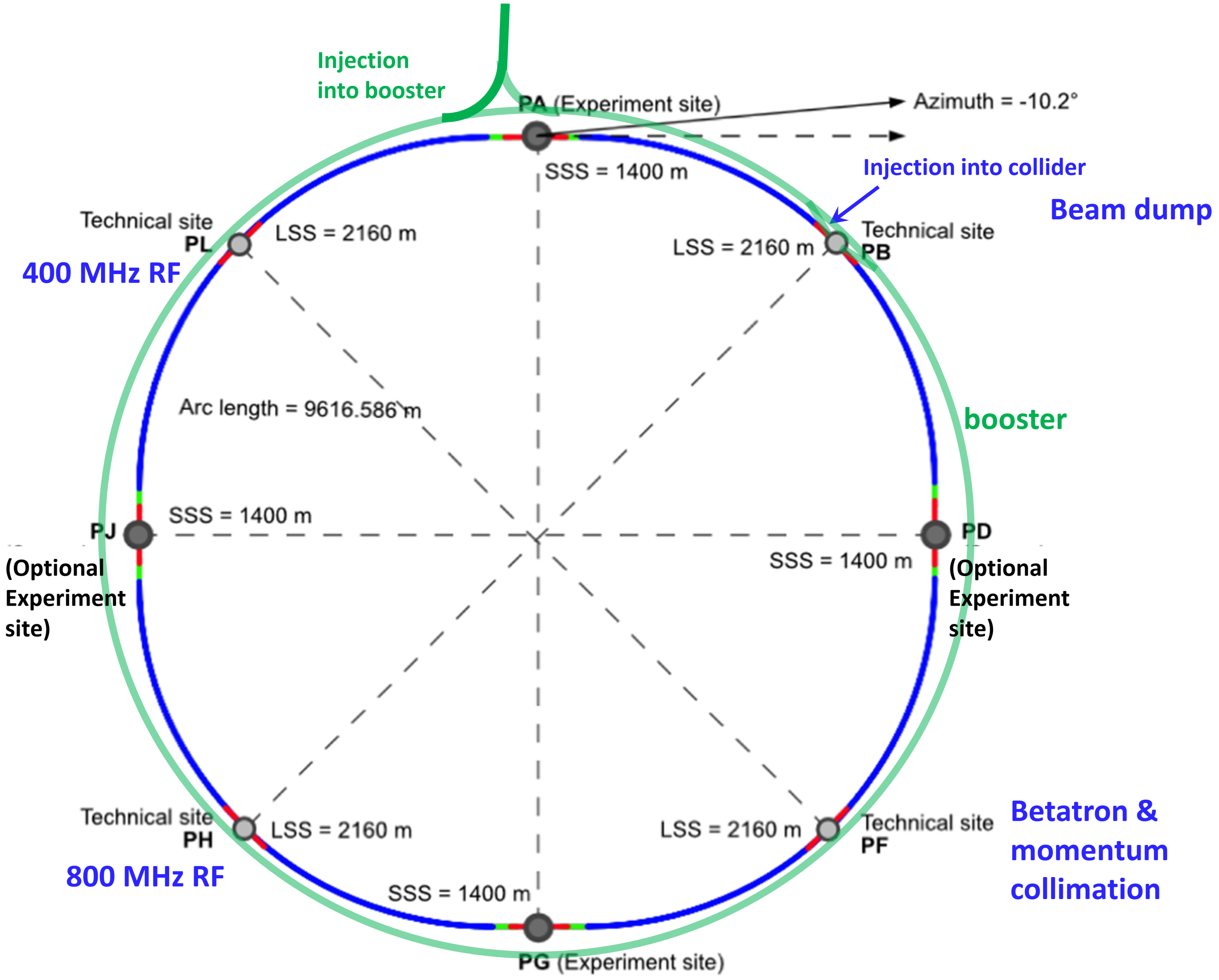


e+e- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
COM energy	250 GeV	0.38, 1.5, 3 TeV	90-365 GeV	90 -250 GeV	250-550 GeV
Lumi (10^{34} cm^{-2}s^{-1})	1.35	1-2	7	4	1.3-2.4
Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



FCC-ee

*Modern two-ring design (to reach amper currents): benchmark at **KEK-B** and Super **KEK-B** with double-ring e+e– collider with multi-ampere stored currents with over than 1000 bunches, small β_* of down to 0.8mm, top-up injection as well as a 22 mrad crossing angle at the IP with crab crossing!*

CepC similar design (in China)

e^+e^- Collider Projects - Circular

Project	ILC	CLIC	FCC-ee	CepC	C^3
Location	Kitakami - JP	CERN	CERN	China TBD	Japan - US?
Length	20.5 km	11-50 km	90-100 km	100 km	8 km
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Int. Lumi	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}	~2 ab^{-1}

Large amount of extremely useful data in a very clean environment!

- 100 000 Z / second
- 10 000 W / hour
- 1 500 Higgs bosons / day
- 1 500 top quarks / day

Event statistics (4IP)

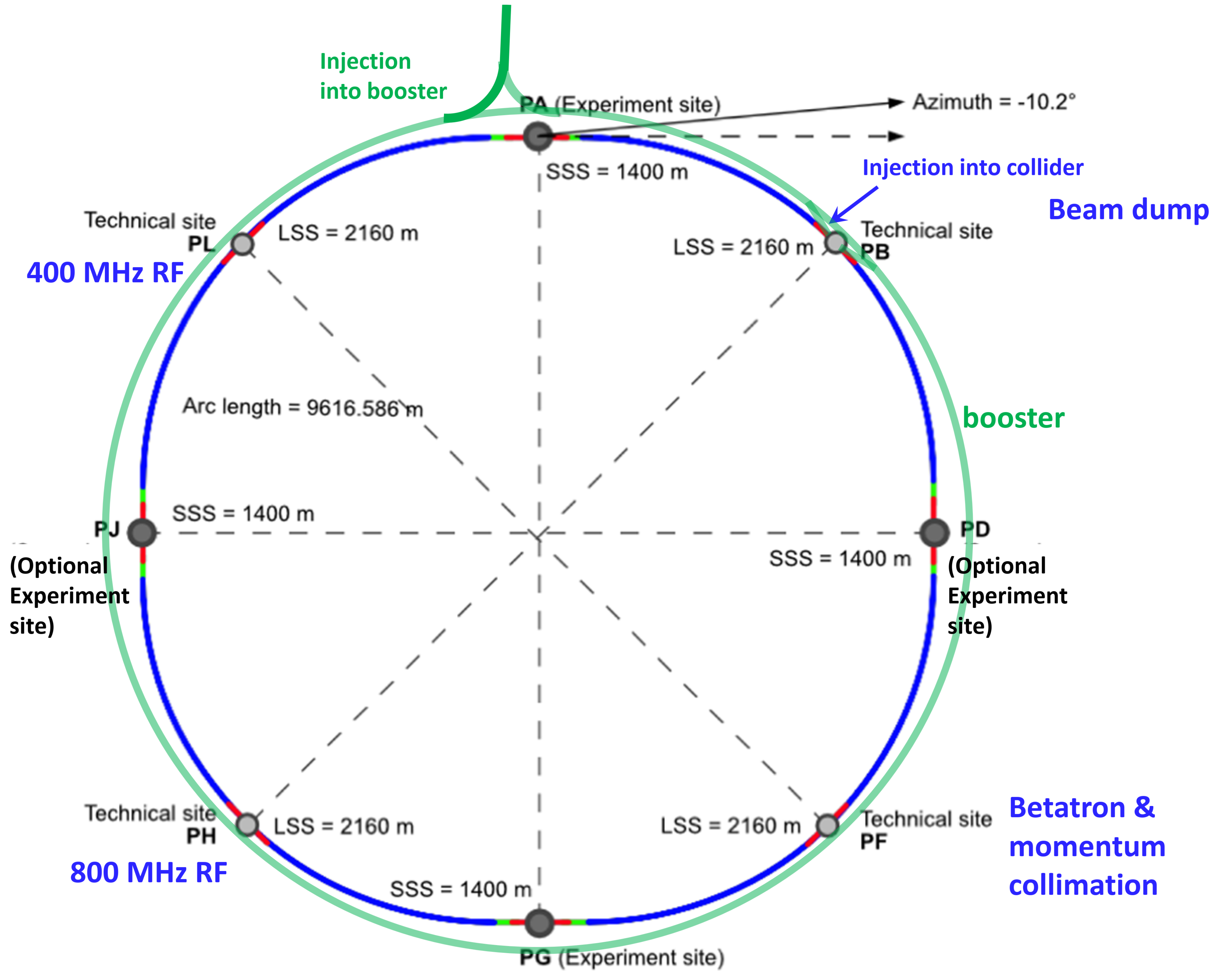
					E_{CM} errors	
Z peak	E_{cm} = 91 GeV	4yrs	6.10^{12}	$e^+e^- \to Z$	<100 keV	**LEP x 3.10^5**
WW threshold	$E_{cm} \geq$ 157-161	2yrs	2.10^8	$e^+e^- \to WW$	<300 keV	**LEP x 2.10^3**
ZH maximum	E_{cm} = 240 GeV	3yrs	$1.5\ 10^6$	$e^+e^- \to ZH$	1 MeV	**Never done**
s-channel H	$E_{cm} = m_H$	*(3yrs?)*	*O(5000)*	$e^+e^- \to H$	<< 1 MeV	**Never done**
Top production	E_{cm} = 340-365 GeV	5yrs	2.10^6	$e^+e^- \to t\bar{t}$	2 MeV	**Never done**

*From A. Blondel

Precision on m_H of ~3 MeV

FCC-ee Future Circular Collider are CERN

~91 km Design with 4 interaction points



One LEP produced every 3 minutes!!

CepC similar design (in China)

e^+e^- Collider Projects

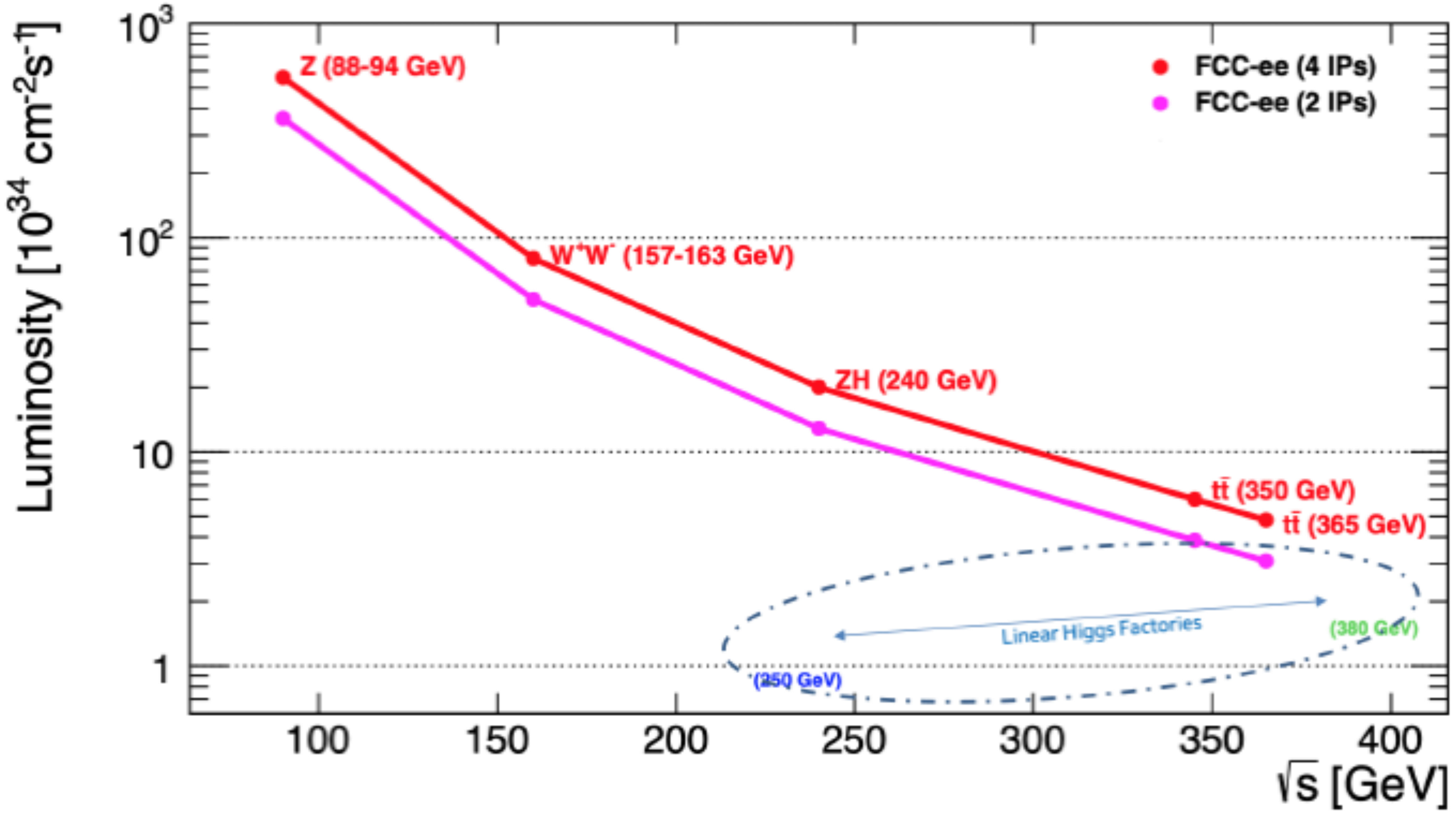
Future e+e- projects are complementary

- Circular colliders provide massive amount of data to address the Higgs and EW scale precision needs (1)
- Linear colliders could address specific questions more the need to explore higher energies (2)

FCC is an integrated program including FCC-hh phase - “The best project for CERN”

FCC-ee intensity provides vast opportunities

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- x10 improvement on Belle II statistics for b, c and τ
- Huge direct discovery potential for feebly interacting particles in the 5-100 GeV range



Clear advantage of circular and 4 IP in terms of luminosity!

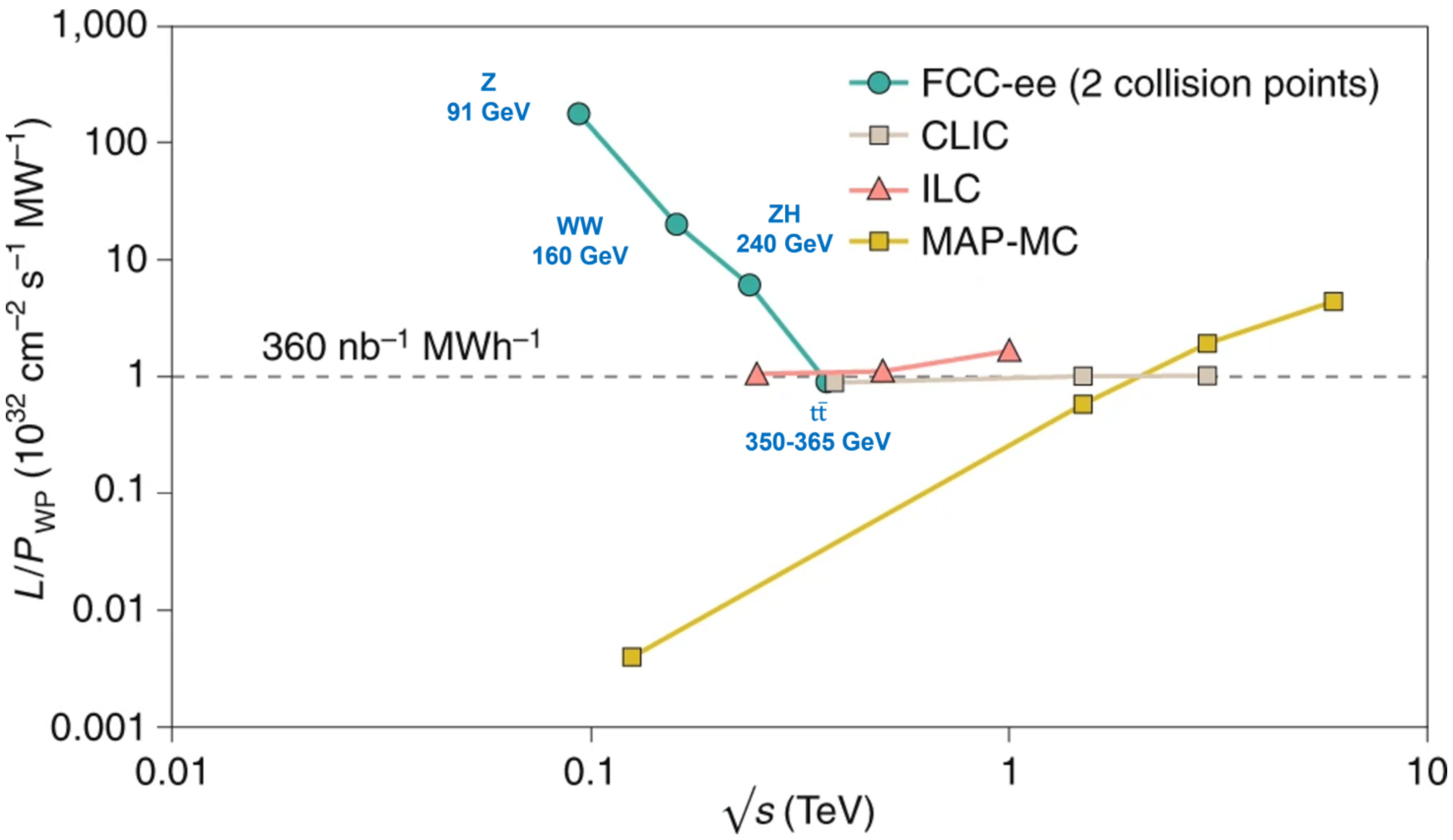
e+e- Collider Projects

Outstanding issues

- Timescales:
  - Projects outside CERN: ILC (**2038**) and CepC (**2035**)
  - Projects at CERN: FCC-ee and CLIC (**2048**)
- Sustainability, Energy and Power consumption are key parameters

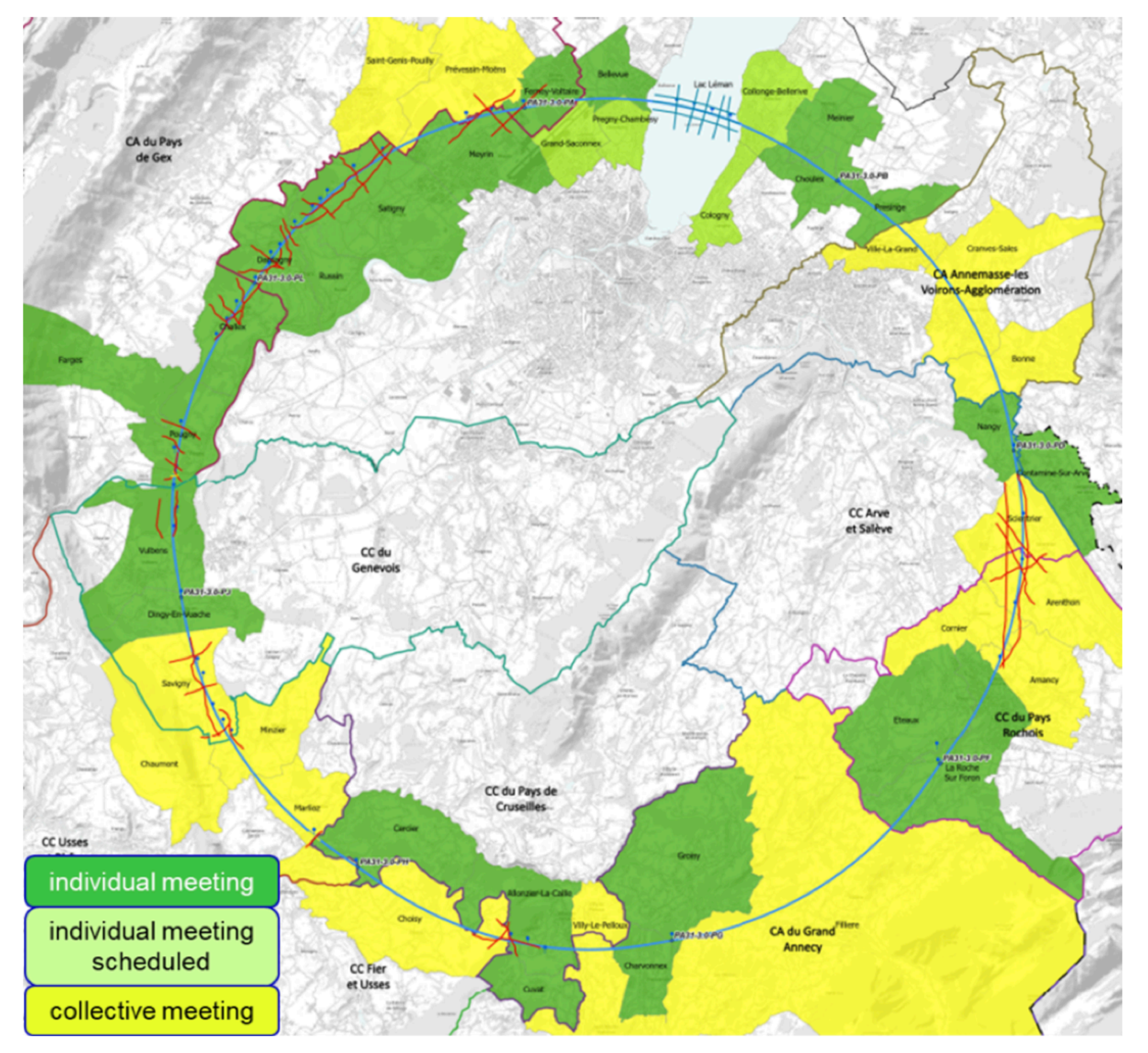
Challenging ideas to the FCC-ee

- An upgrade of e+e– collisions to higher energies, ~600 GeV or beyond, has been proposed through converting the FCC-ee into a few-pass ERL (Physics Letters B 804 (2020) 135394).
- Monochromatisation could give access to the s-channel Higgs production and thus the electron Yukawa! Understudy.

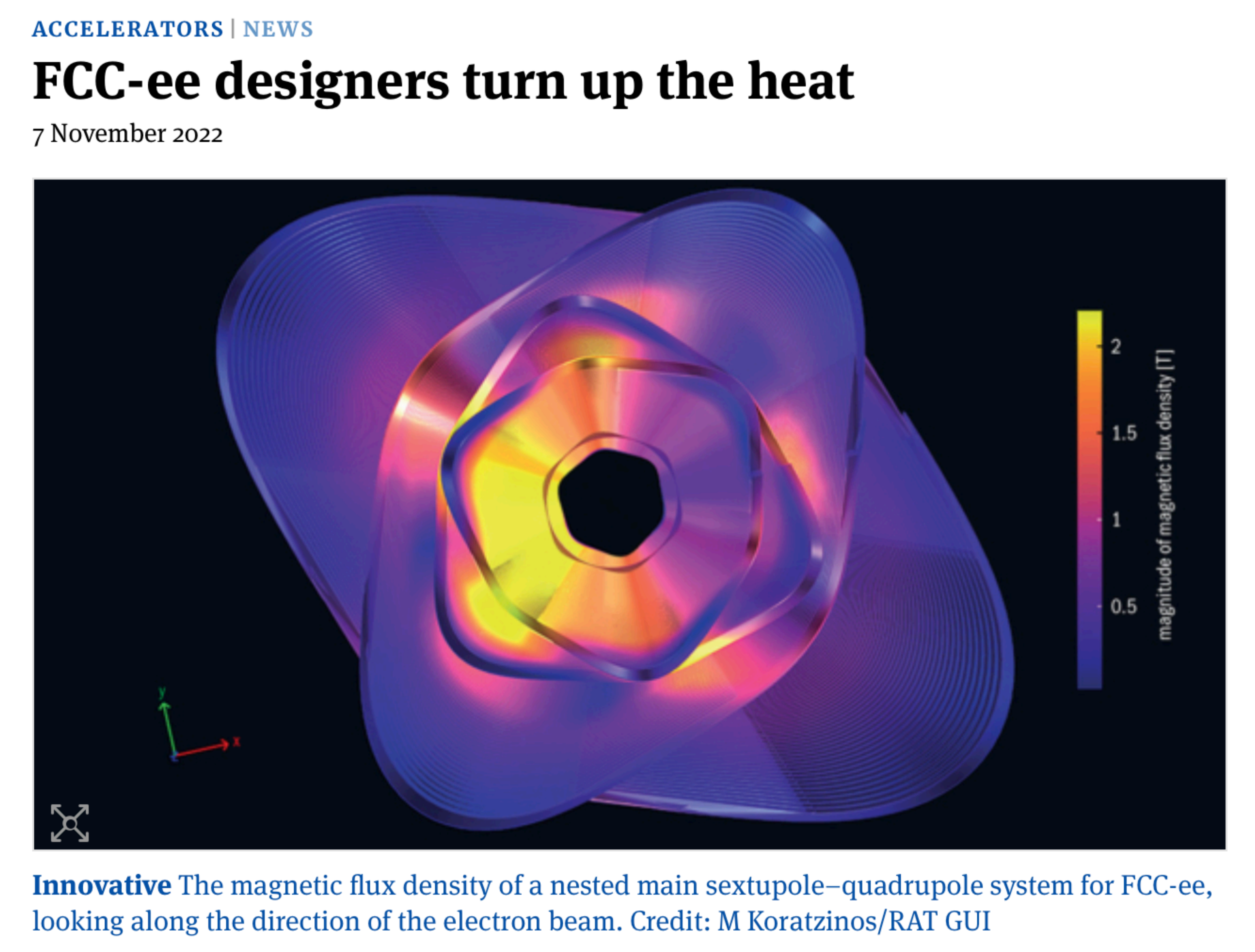


Large uncertainties see Snowmass white paper

Feasibility Studies



- Choice of baseline layout (90.7 km) - discussions with local authorities, environmental investigations and civil engineering designs well under way.
- In particular studies of possible injection schemes article



ACCELERATORS | NEWS

FCC-ee designers turn up the heat

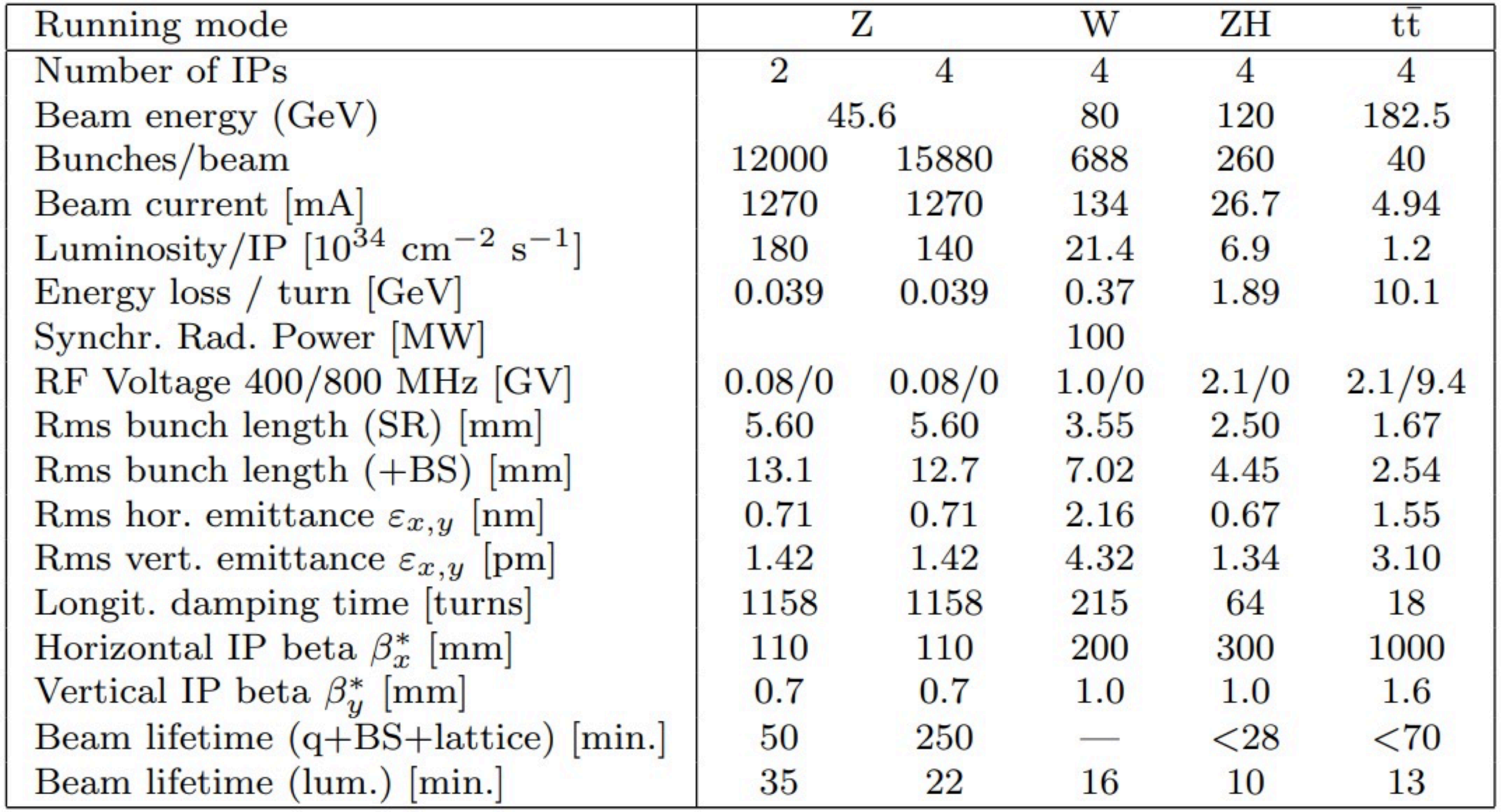
7 November 2022

Innovative The magnetic flux density of a nested main sextupole–quadrupole system for FCC-ee, looking along the direction of the electron beam. Credit: M Koratzinos/RAT GUI

Power consumption

- 240 GeV the instantaneous power is 291 MW (compared to 140 MW for ILC and 110 MW for CLIC for less luminosity)
- Replace 5800 quadrupole and 4672 sextuple normal conducting magnets by HTS CCT magnets! article

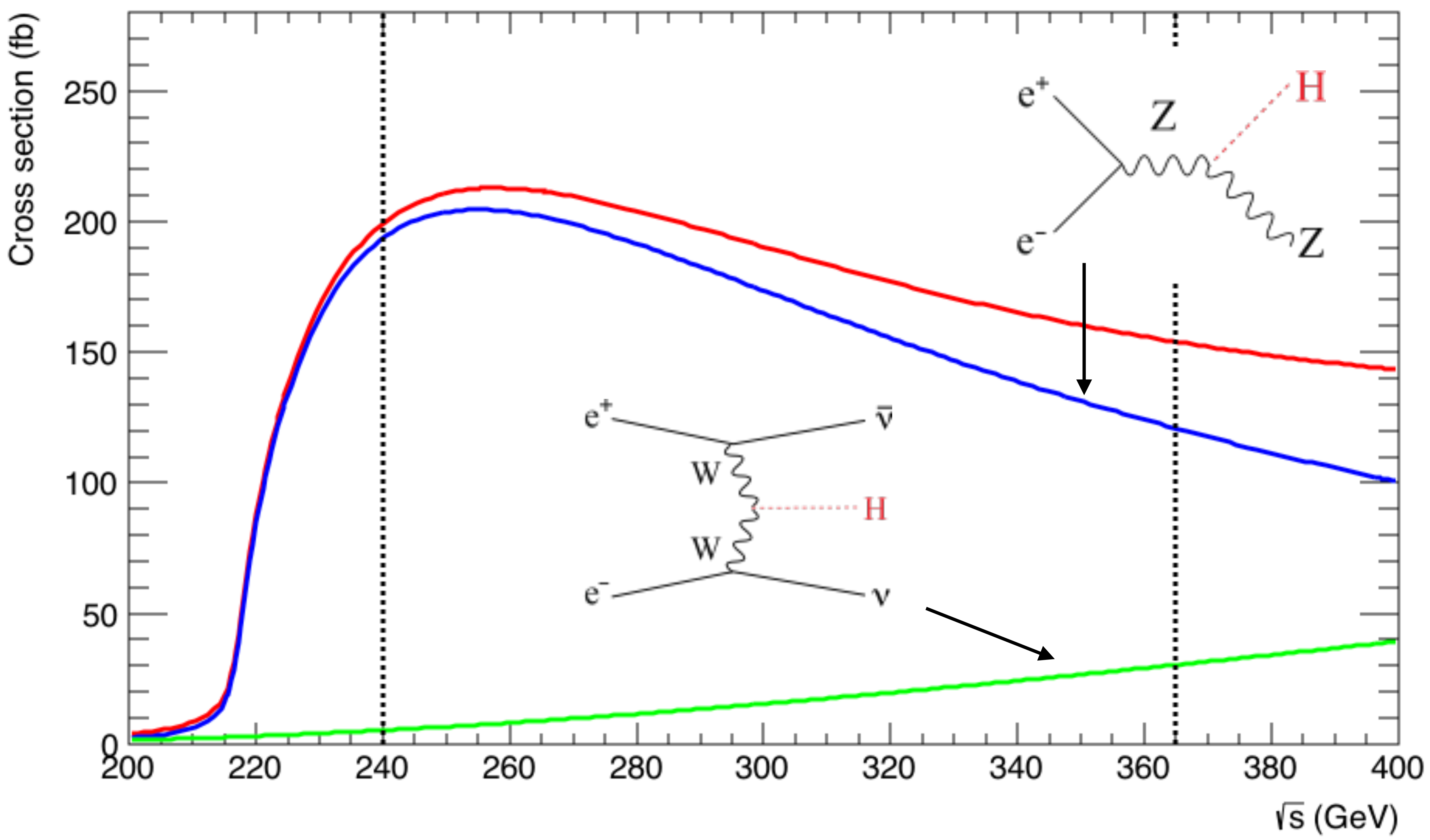
Machine Parameters



Running mode	Z		W	ZH	$t\bar{t}$
Number of IPs	2	4	4	4	4
Beam energy (GeV)	45.6		80	120	182.5
Bunches/beam	12000	15880	688	260	40
Beam current [mA]	1270	1270	134	26.7	4.94
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	180	140	21.4	6.9	1.2
Energy loss / turn [GeV]	0.039	0.039	0.37	1.89	10.1
Synchr. Rad. Power [MW]	100				
RF Voltage 400/800 MHz [GV]	0.08/0	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	5.60	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	13.1	12.7	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	0.71	2.16	0.67	1.55
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	1.42	4.32	1.34	3.10
Longit. damping time [turns]	1158	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	110	200	300	1000
Vertical IP beta β_y^* [mm]	0.7	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	250	—	<28	<70
Beam lifetime (lum.) [min.]	35	22	16	10	13

4 years   2 yrs   3 yrs   5 yrs

Higgs Physics at e^+e^- Colliders



1.5M per IP very clean ZH events produced at threshold

Approximately 1/3 of the number of ZH events at HL-LHC but in a much cleaner environment!

All final states can be very cleanly reconstructed.

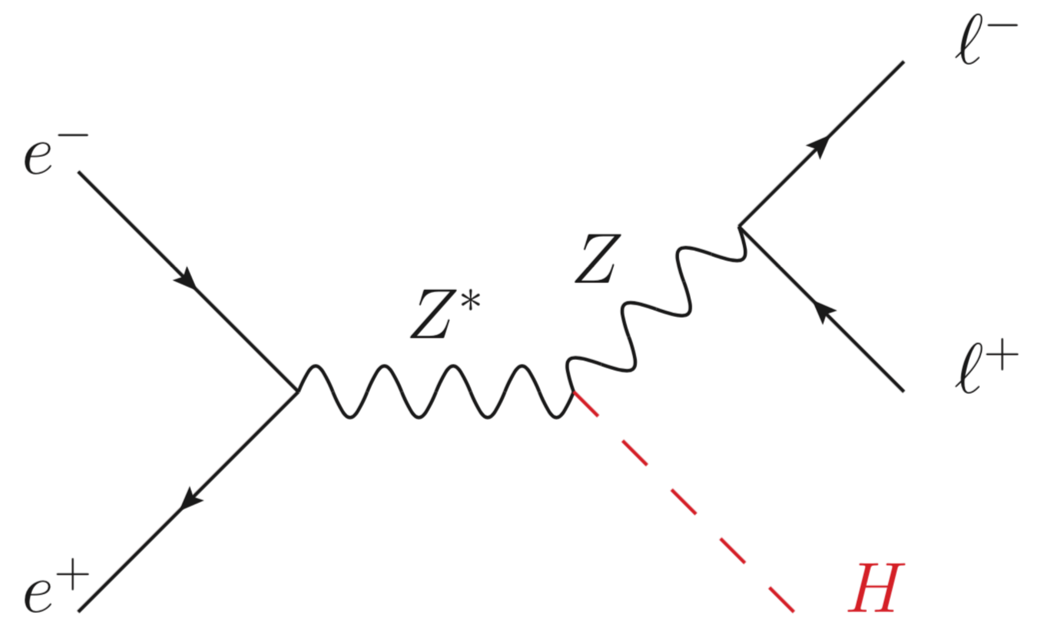
Additional 200k events at 350-365 GeV with approximately 30% from WW fusion which is interesting for the width measurement

- Measure $\sigma(e^+e^- \to HZ) \times Br(H \to bb, cc, gg, WW, \tau\tau, \gamma\gamma, \mu\mu, Z\gamma, \ldots)$ from each individual final state.
- Can also measure invisible decays from the reconstructed Z boson.

Fundamental difference with the LHC (and other hadron colliders): the width can be measured from the total HZ cross section! **Coupling measurements are less model dependent!**

Higgs Physics at e$^+$e$^-$ Collider

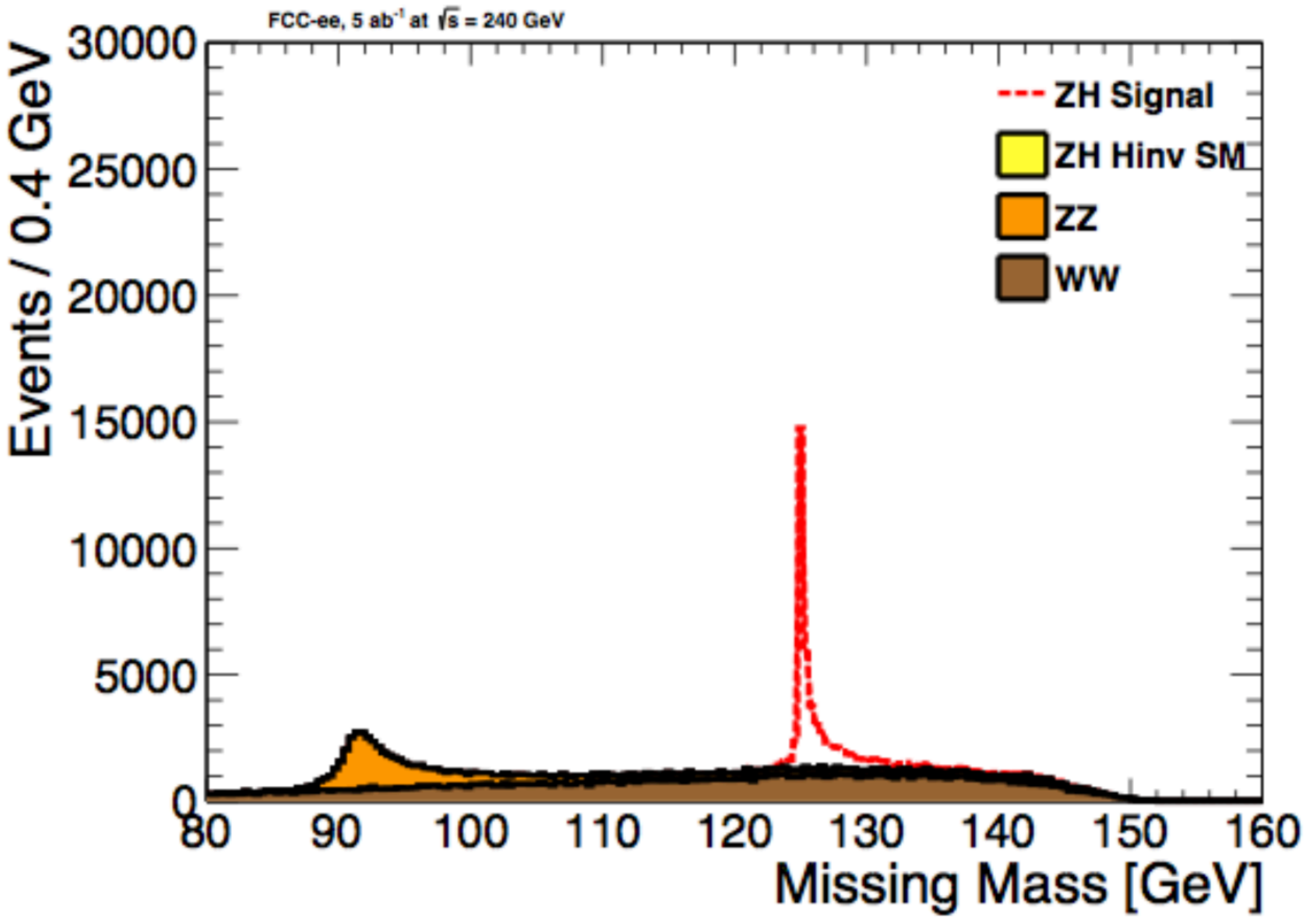
Threshold production of HZ provides a unique opportunity to measure the total HZ cross section through the recoil method



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |p_{\ell\ell}|^2$$

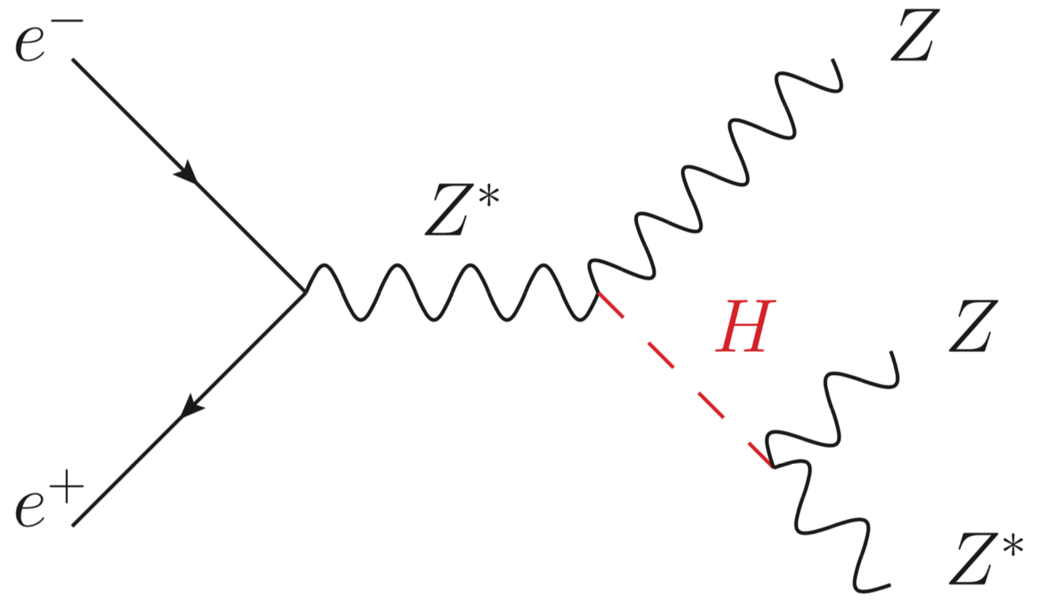
From conservation of energy and momentum, the energy and momentum of the Higgs is known from the Z without measuring the Higgs boson!

$$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$$



Measurement of the cross section at 240 GeV at 0.5% precision (0.9% at 365 GeV).

Then using the measurement of HZ with the Higgs to ZZ*:

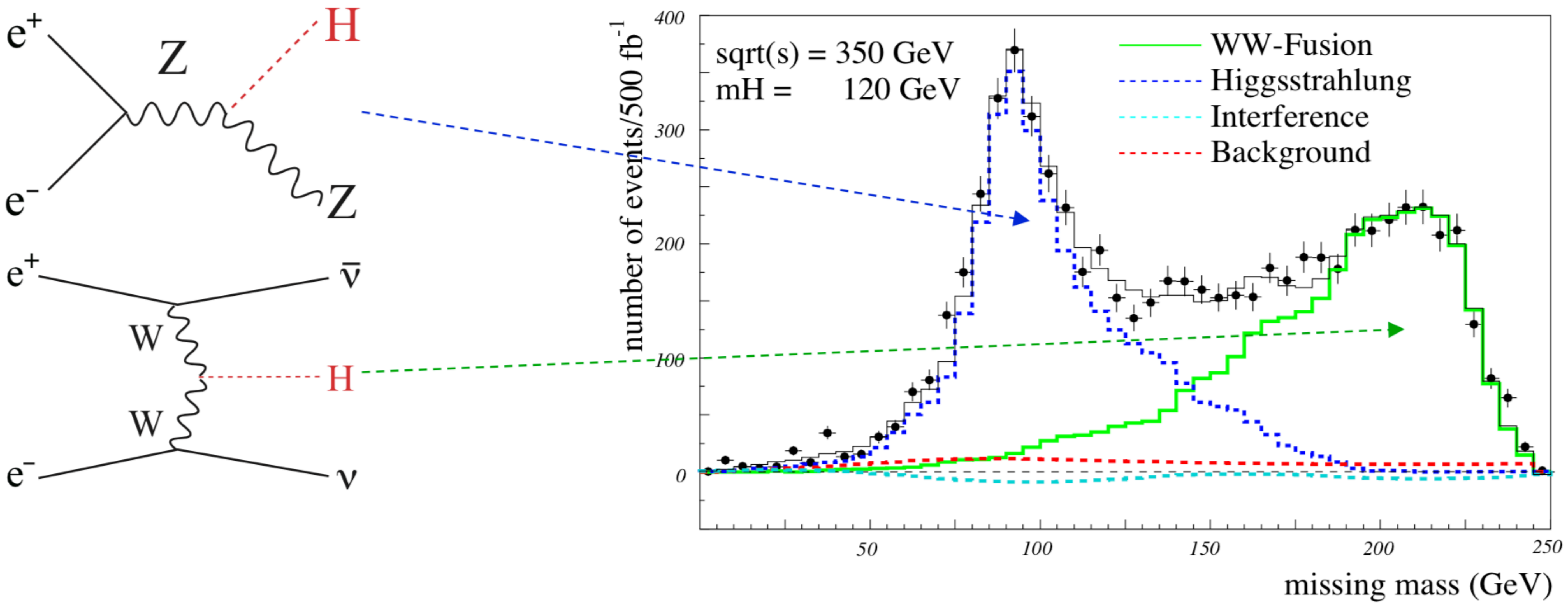


The total width of the Higgs can be measured at ~**2.5%** level with FCC-ee (240) alone.

$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

Higgs Physics at e+e- Collider

Further measurements of the width can be obtained using the WW fusion process as follows:



The WW fusion can be disentangled from the HZ process from the missing mass (which will not be peaked at the Z, but in this case at sqrt(s)-mH.

Then from the ratio of the following three measurements:

$$\frac{[\sigma(ZH)\times B(H\to WW)]\times[\sigma(ZH)\times B(H\to bb)]}{\sigma(\nu\nu H)\times B(H\to bb)}$$

Use different energy scale assumptions!

$$\propto \frac{\kappa_Z^2\kappa_W^2}{\Gamma_H}\times\frac{\kappa_Z^2\kappa_b^2}{\Gamma_H}\times\frac{\Gamma_H}{\kappa_W^2\kappa_b^2}=\frac{\kappa_Z^4}{\Gamma_H}$$

Substantial gain in sensitivity to the total width, using higher COM energies and adding FCC-ee (365)!

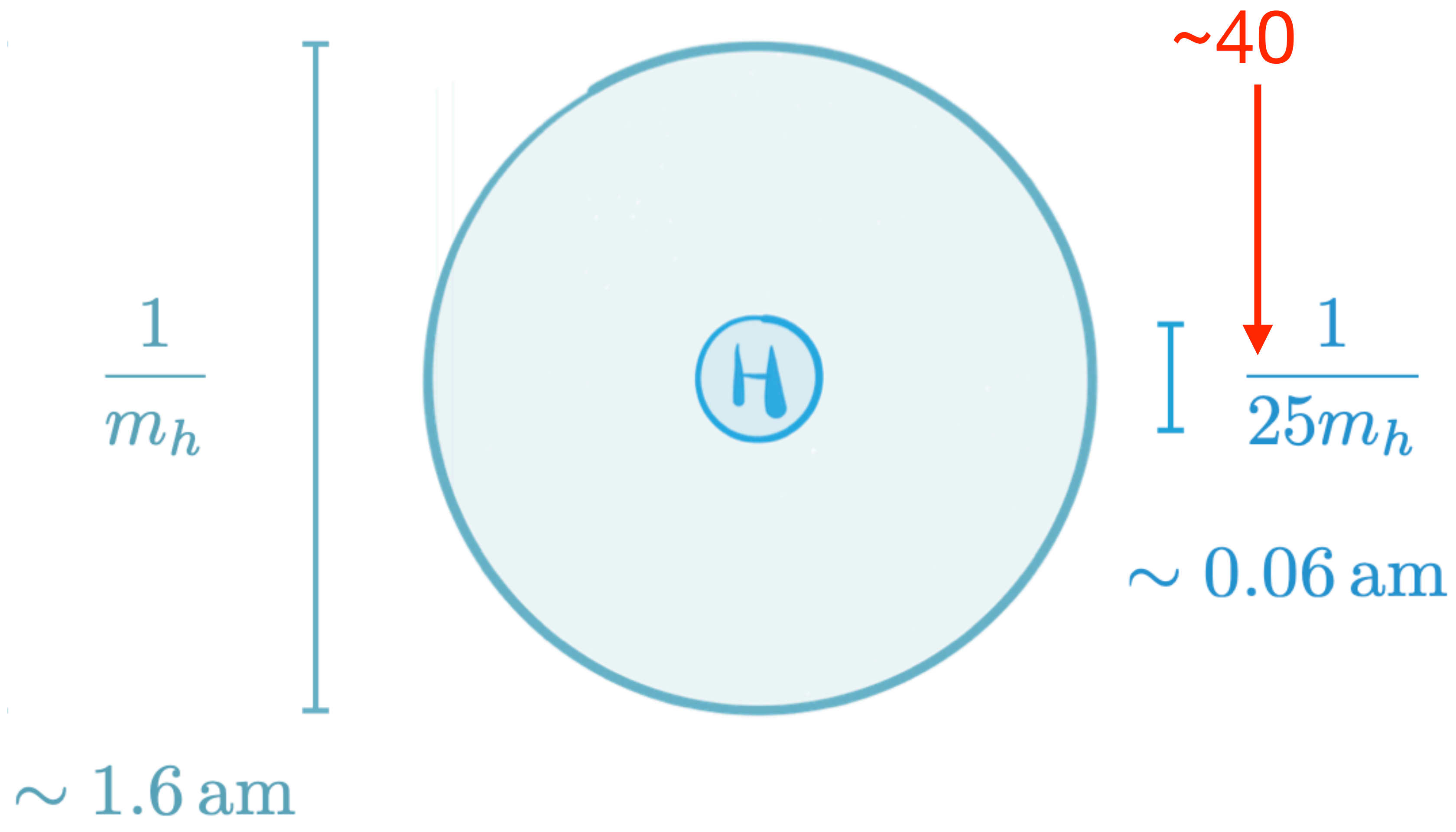
Precision on Γ_H of 1.1%

Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	Current precision	HL-LHC	FCC-ee (only)
κ_γ	13%	6%	1.8%	3.9%*
κ_W	11%	6%	1.7%	0.4%
κ_Z	11%	6%	1.5%	0.2%
κ_g	14%	7%	2.5%	1%
κ_t	30%	11%	3.4%	-
κ_b	26%	11%	3.7%	0.7%
κ_c	-	-	40%	1.3%
κ_τ	15%	8%	1.9%	0.7%
κ_μ	-	20%	4.3%	8.9%*
$\kappa_{Z\gamma}$	-	30%	9.8%	-*
B_{inv}		11%	2.5%	0.2%

***Of course not competitive on rare decays.**

Far more stringent constraint on the size of the Higgs boson!



$$c_H \frac{v^2}{\Lambda^2} < 0.002$$

Taking $c_H = 1$ leads to $\Lambda > 5.5$ TeV

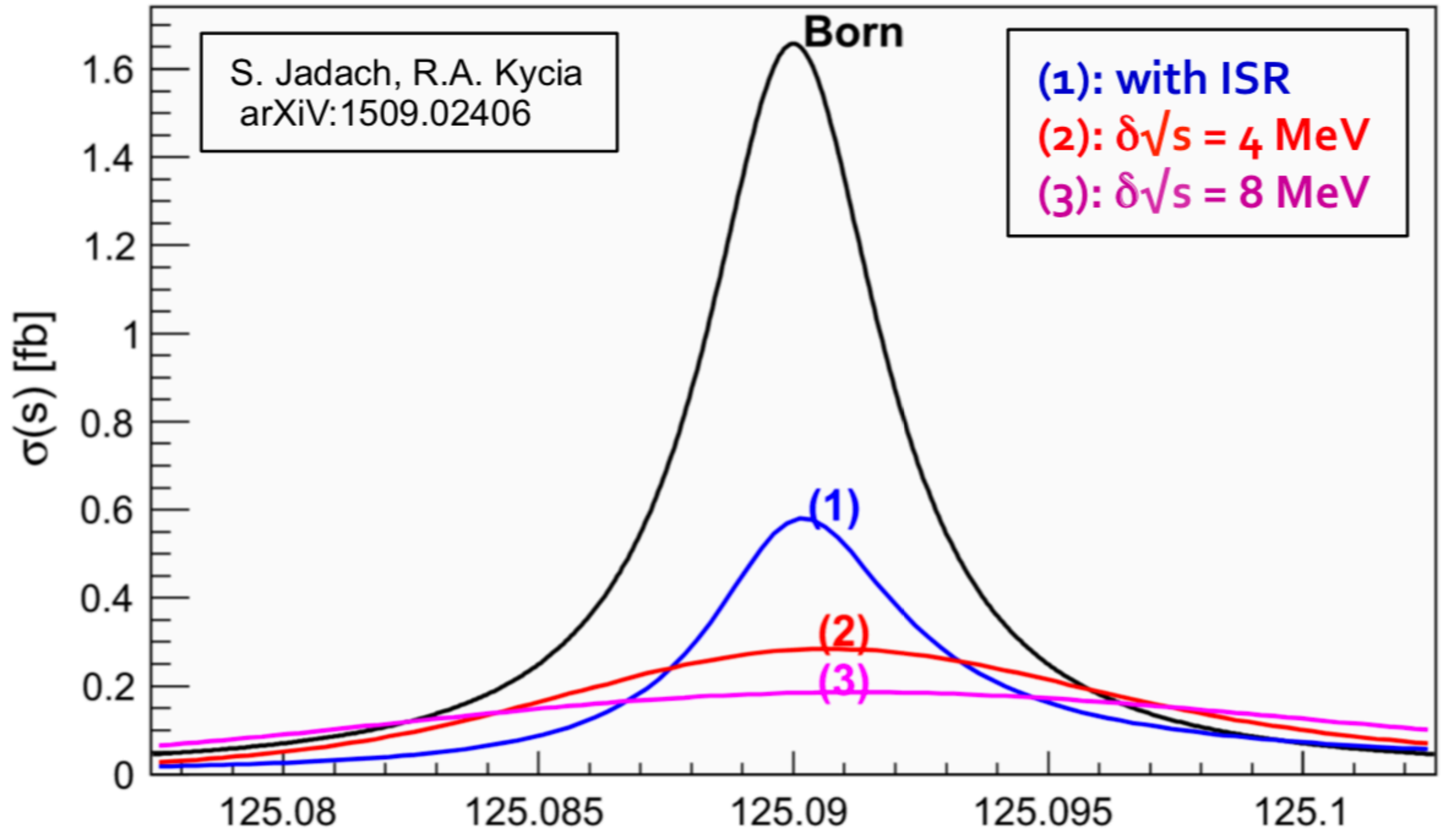
s-Channel Higgs production and e-Yukawa

Extremely challenging for several reasons:

1.- The production cross section is $\sigma(ee \to H) = 1.6\ \mathrm{fb}$ will require extremely large luminosities

2.- Given the Higgs width of 4.2 MeV, and extremely small energy spread is necessary - require monochromatization.

- Default beam spread has delta ~ 100 MeV (no visible resonance)
- Requires beam monochromatisation
- Requires a prior knowledge of the Higgs boson mass of ~couple of MeV at most!
- Would require huge luminosity and therefore 4IPs.



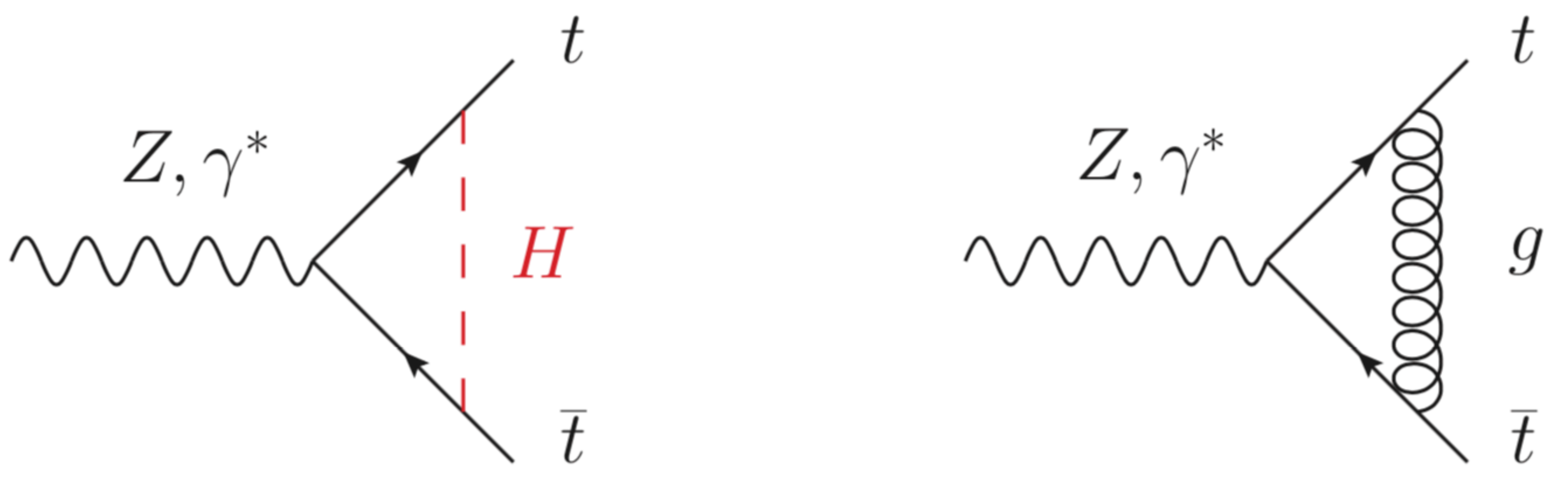
First studies indicate a sensitivity of 0.4σ per year and per detector (spread of ~6 MeV)

Monochromatization already considered but never used

Monochromatization uses opposite correlation between spatial position and energy.

Model Dependent Measurements through Loops

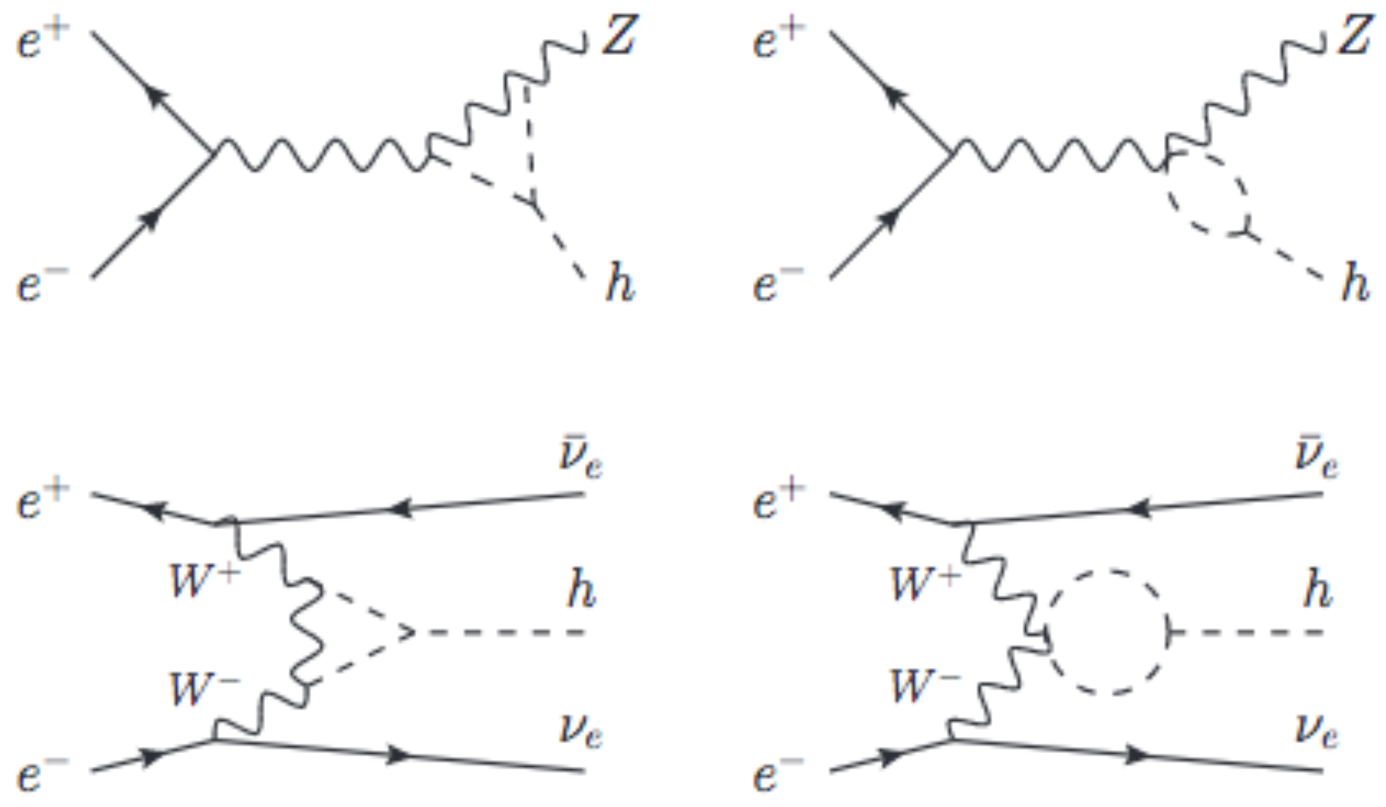
Top pair cross section at threshold and above

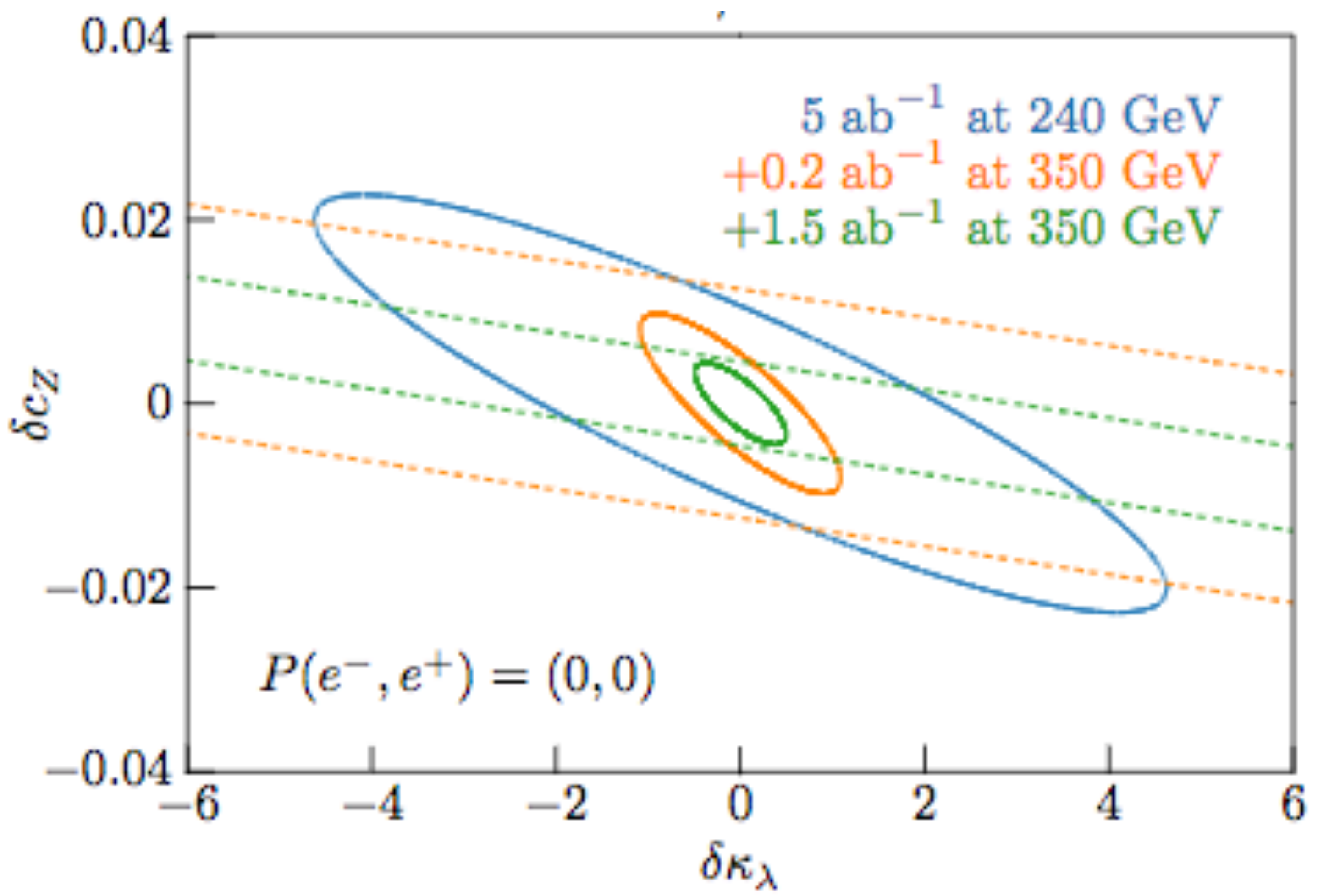


Precision on alphaS at FCC-ee will be important

Top Yukawa coupling precision from top pair cross section measurements **<10%**

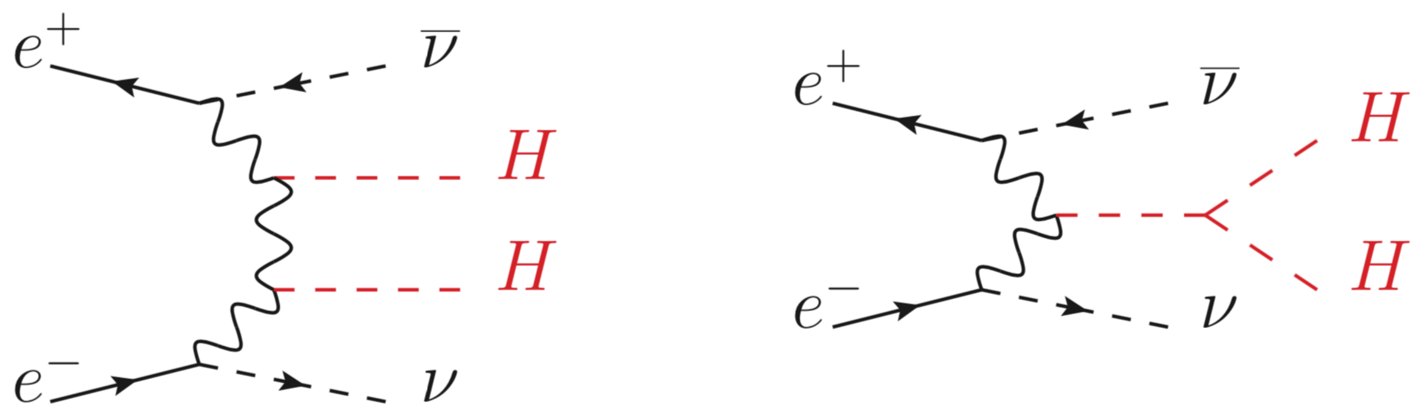
Higgs cross section at 240, 350, at 365 GeV





Higgs self coupling precision **~30%** - reduced to ~20% with kappaZ = 1 from SM

Similar precisions are obtained with double Higgs production at CLIC (√s = 1.4 and 3 TeV)



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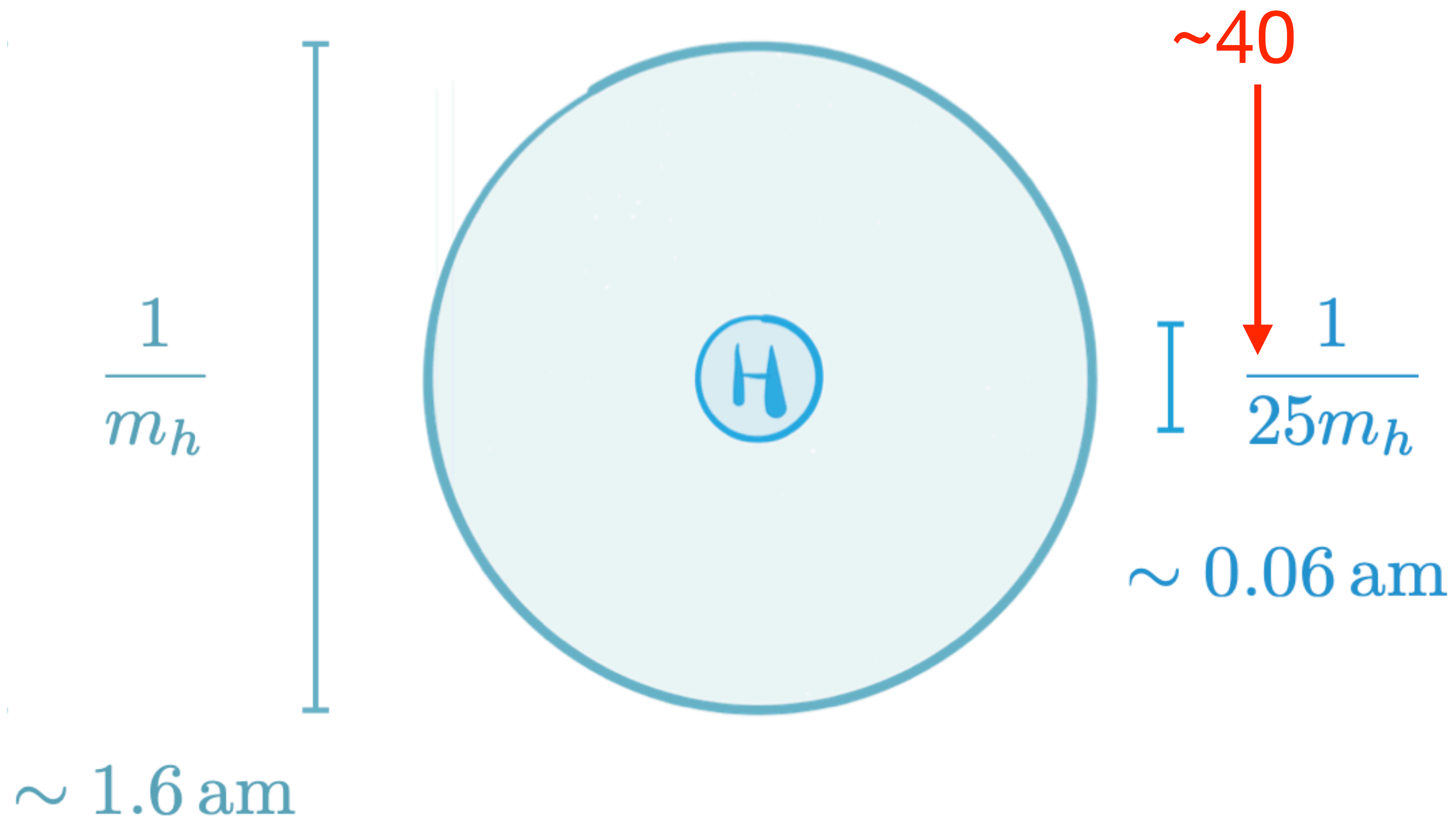
κ_μ	-	20%	4.3%	8.9%
$\kappa_{Z\gamma}$	-	30%	9.8%	-
B_{inv}	-	11%	2.5%	0.2%
κ_λ	-	-	50%	27%*

***Of course not competitive on rare decays.**

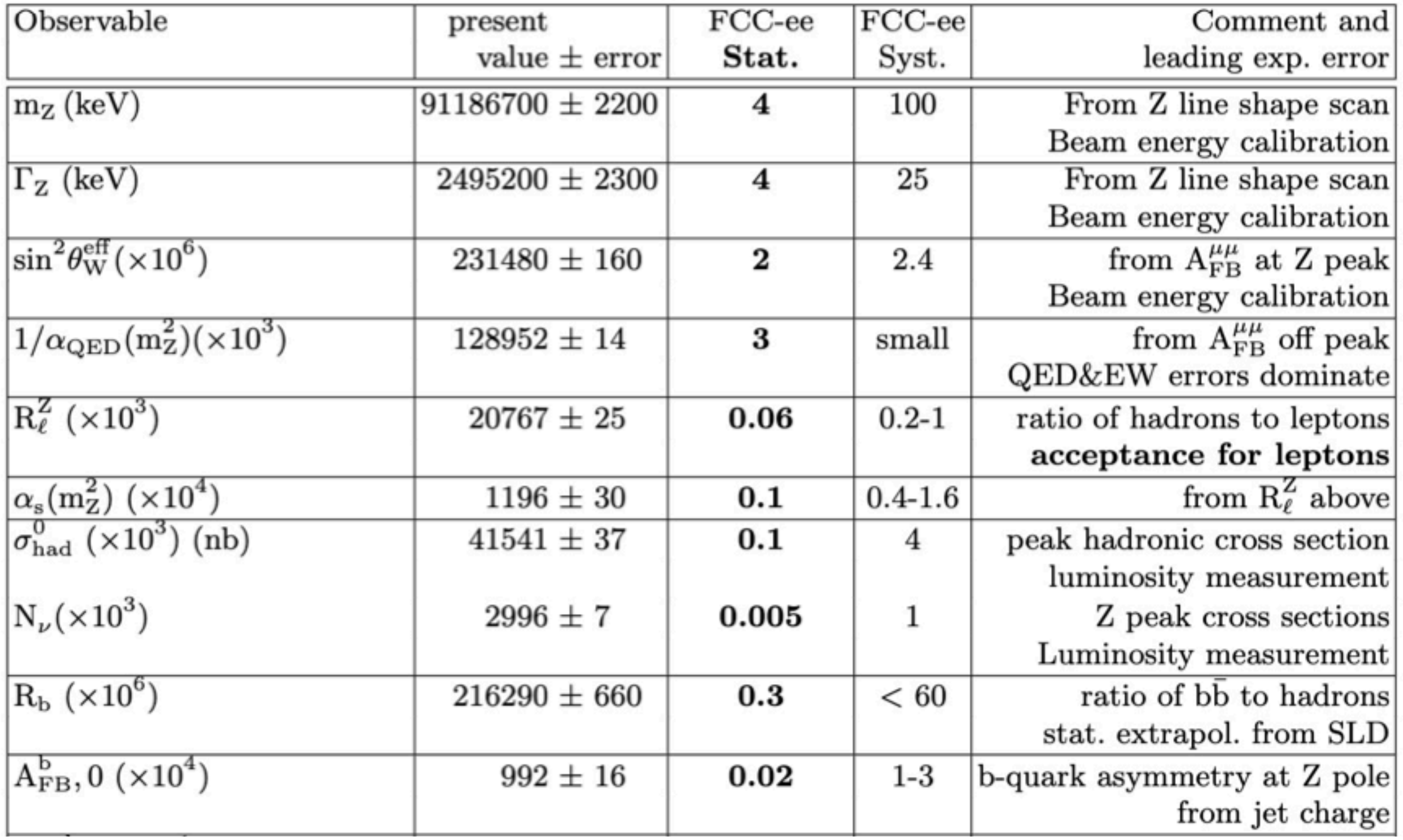
Far more stringent constraint on the size of the Higgs boson!



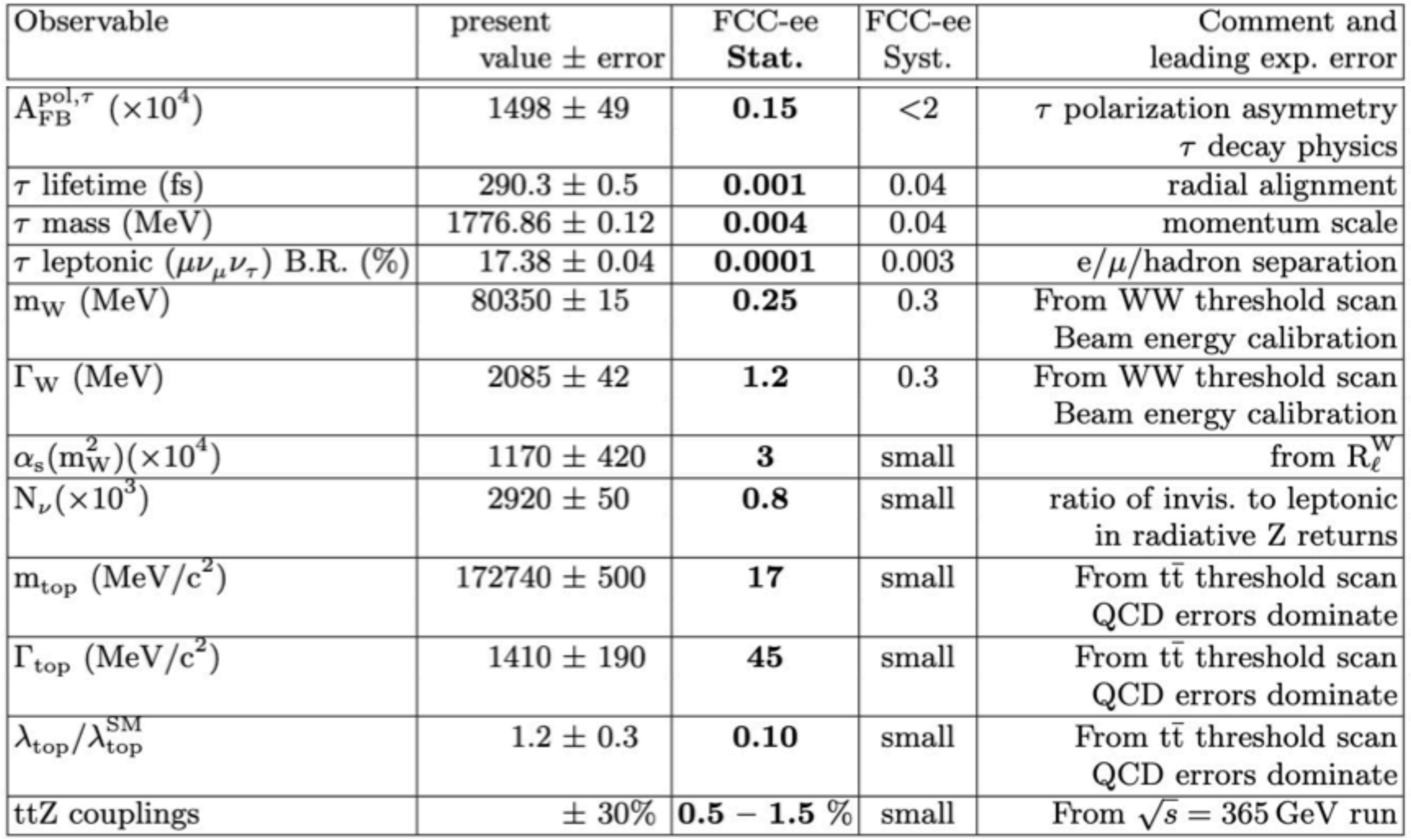
$$c_H \frac{v^2}{\Lambda^2} < 0.002$$

Taking $c_H = 1$ leads to $\Lambda > 5.5$ TeV

e+e- Ultimate Precision Machine!!



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{\mathrm{pol},\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu (\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

EW Precision

Key measurements:

- $m_Z \sim 10^{-6}$, $m_W \sim 10^{-5}$,
  $m_{top} \sim 10^{-4}$
- $sin^2_{\theta_W} \sim 3.10^{-6}$, $\alpha_{QED}(m_Z^2) \sim 10^{-5}$,
  $\alpha_S \sim 10^{-4}$

FCC-ee is much, much more than a Higgs factory!

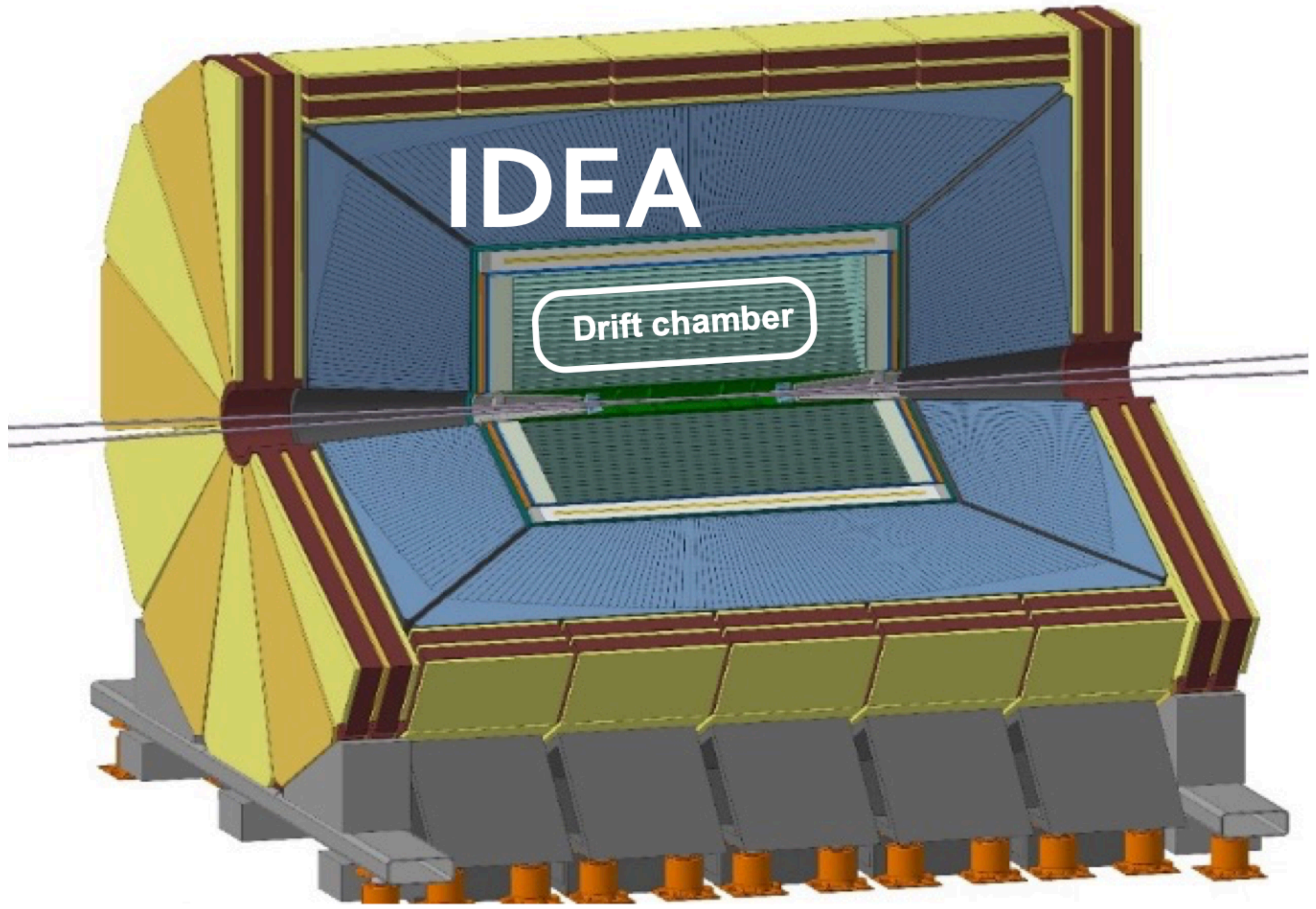
Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- Indirect discovery **potential up to 70 TeV**

e+e- Ultimate Precision Machine!!

Ultimate precision machine requires ultimate precision detectors!

Analysis work is now strongly oriented **towards detector requirements to achieve the design precision**



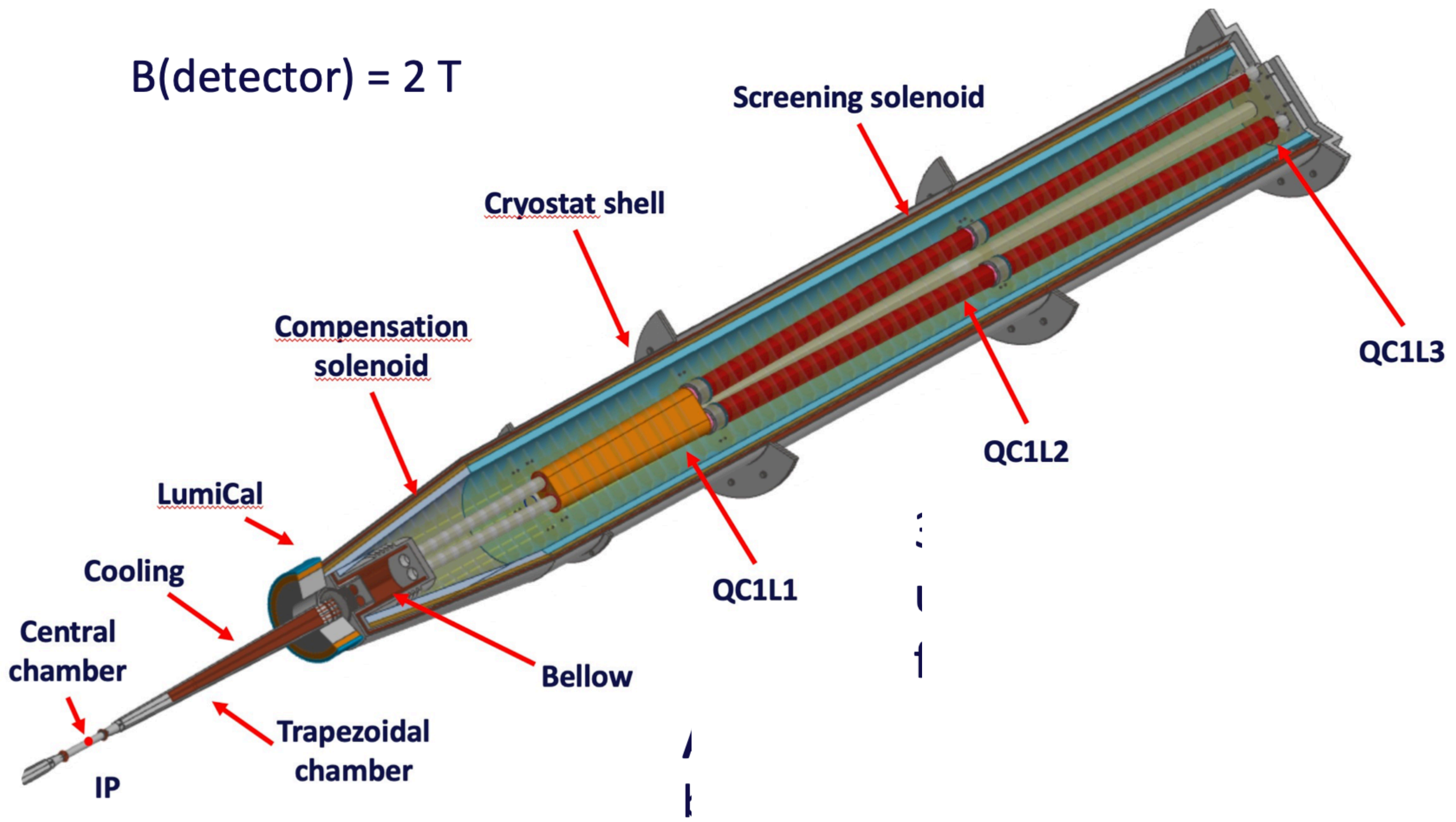
Several detector concepts: **CLD**, **IDEA** and **ALLEGRO** (Nobel Liquid concept)

Key aspects are very small amount of material in the inner detector region for precision track measurements and precise and highly granular calorimeter (numerous concepts)

See talk by Magnus Mager on MAPS!

The FCC-ee interaction region and final focus!

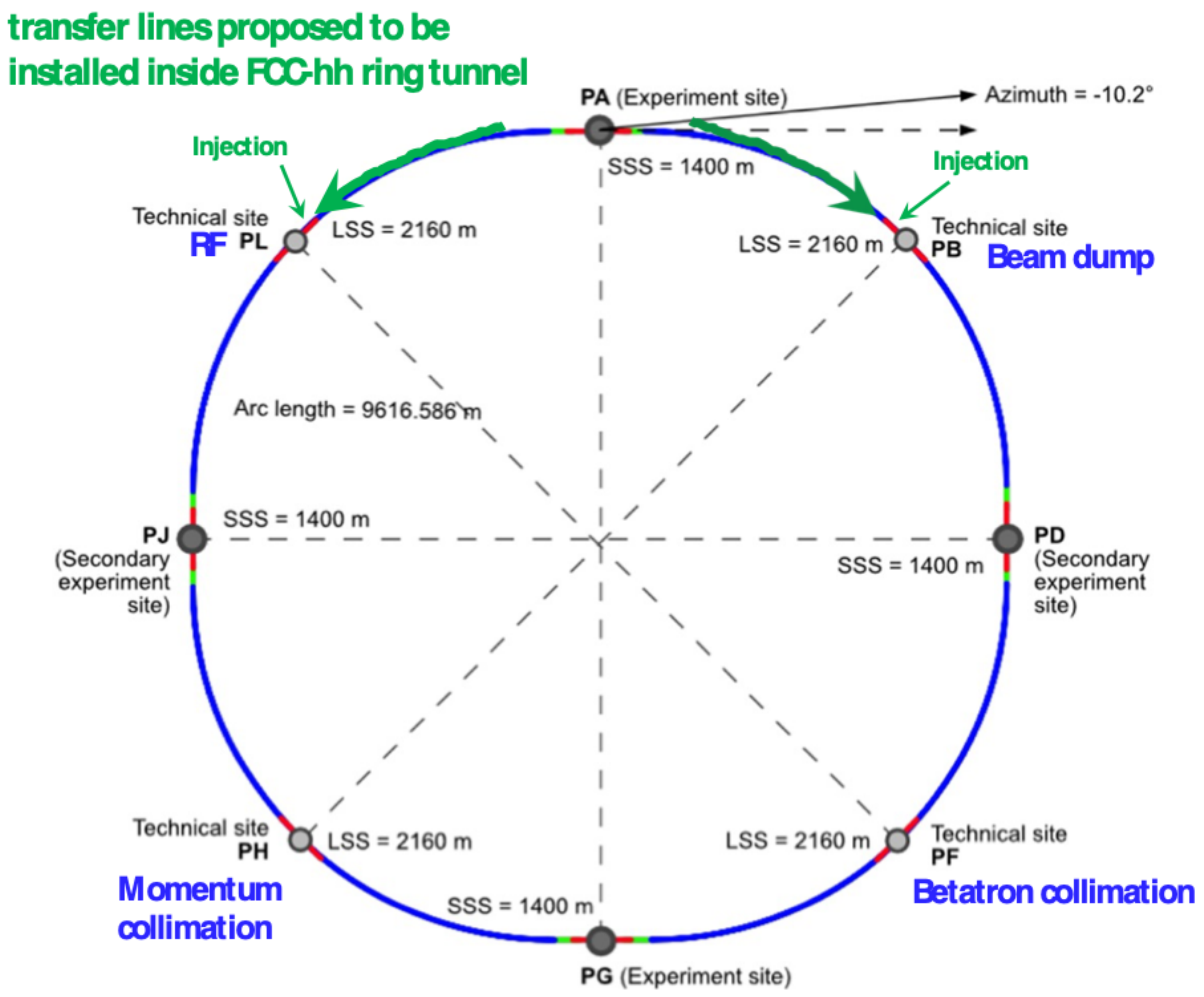
- Critical to reach highest possible luminosities
- Quadrupole magnets and final focus almost entirely inside the detector (at 8.4 m) - very strong requirements to reach **nano beams!**



Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh the second phase of the FCC program

Project	HL-LHC	FCC-hh	SppC
Location	CERN	CERN	China TBD
Circ.	27 km	90 km	55 - 100 km
COM energy	14 (15?) TeV	100 TeV	70 -140 TeV
Lum. (ab^{-1})	3	20-30	TBD
PU	200	1000	TBS
Field	8T	18T	20T



SppC similar design

Key technological challenges

- High field magnets, need 16T to reach 50 TeV/beam - Nb3Sn (FCC-hh) or Nb3Sn with HTS inserts (SppC) - exploration of HTS magnets
- Machine protection 30 W/m synchrotron radiation and **8GJ per beam (equivalent to Boing 747 at cruising speed)**

Hadron Collider Projects - Exploring the Multi-TeV scale

FCC-hh program

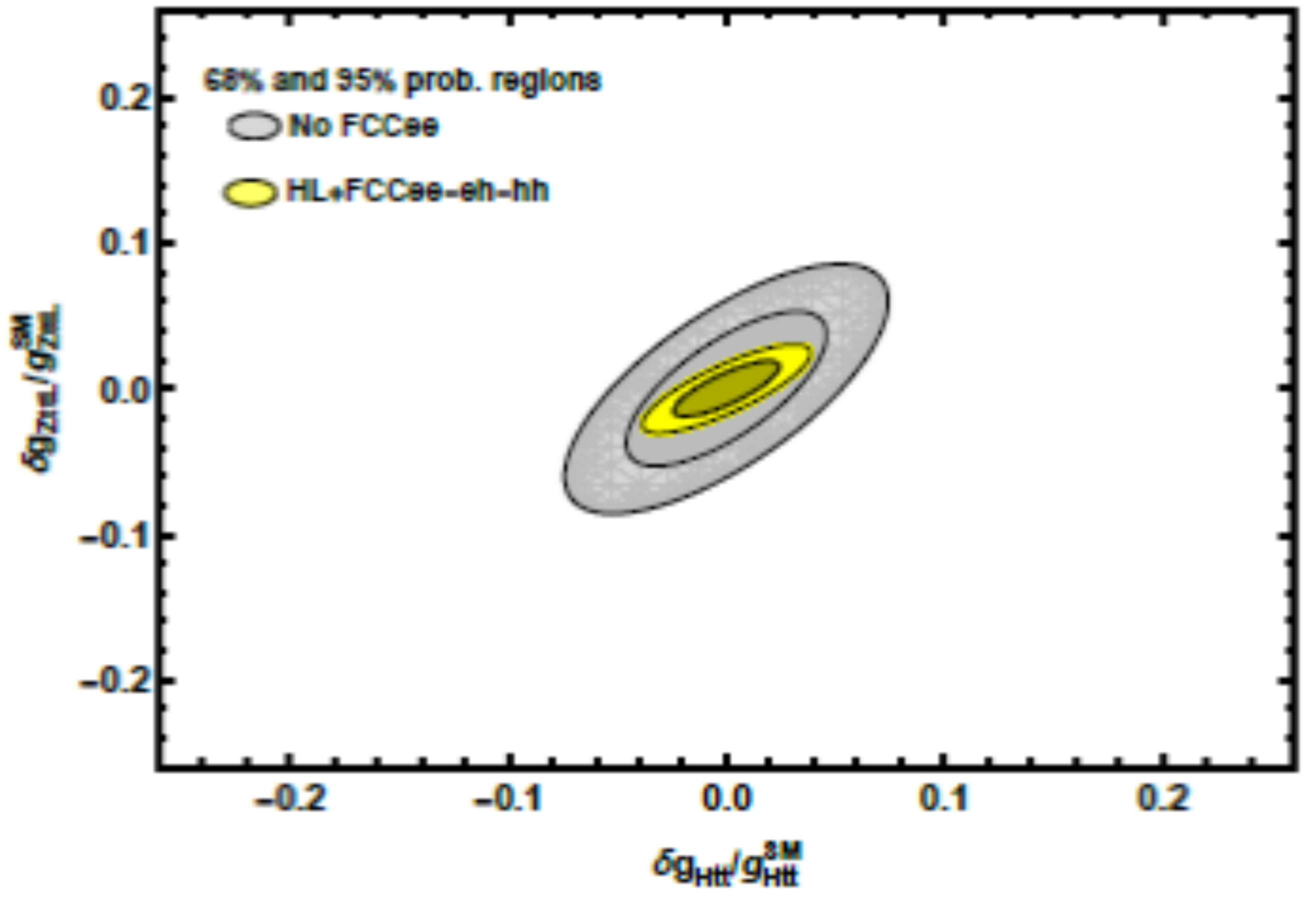
- Primary goal is to explore the Multi-TeV scale with direct searches for new phenomena.
- **Guaranteed deliverables**: completion of the missing key pieces in Higgs precision κ_H and κ_t

Essential complementarity with FCC-ee

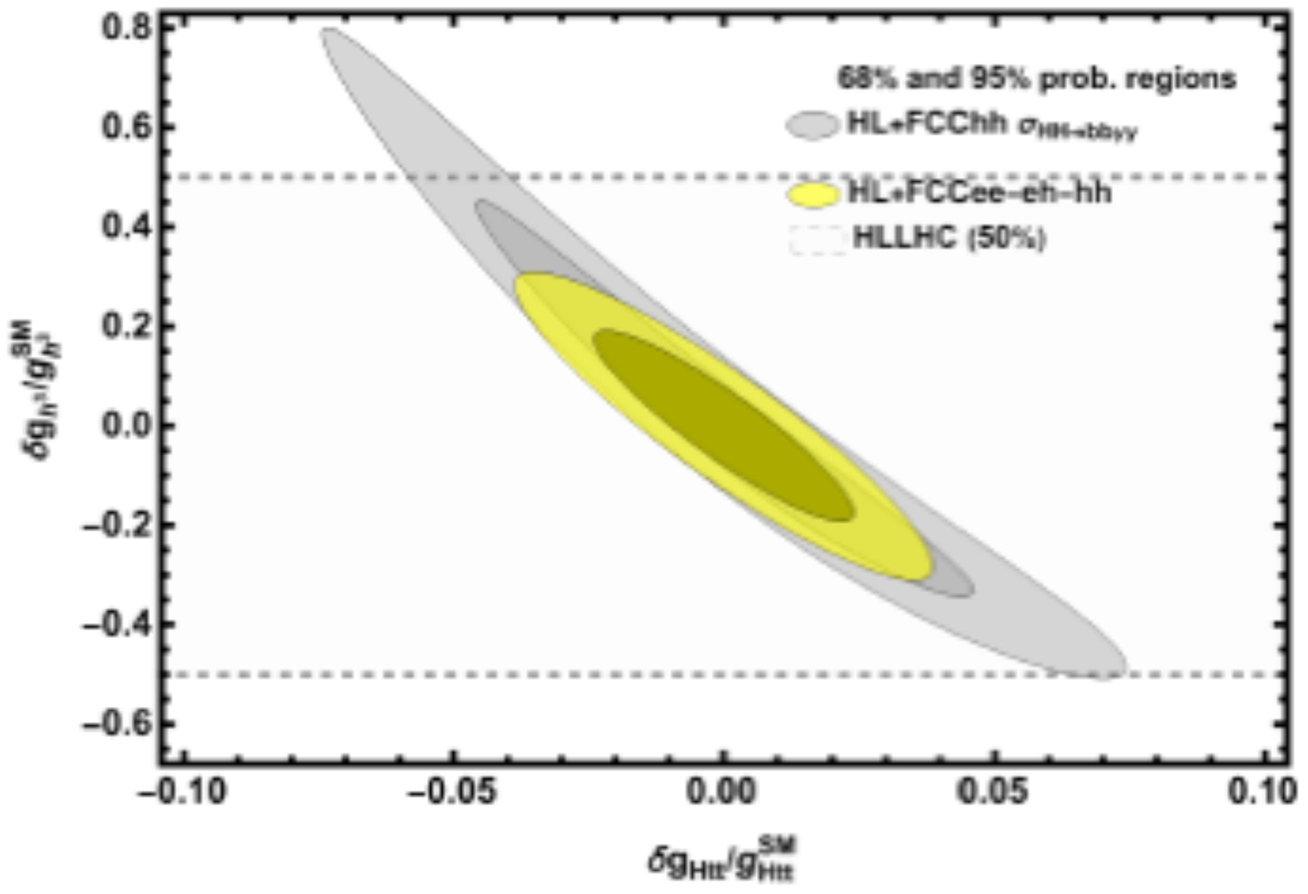
- FCC-hh is a very intricate environment (up to 1000 PU events), event reconstruction at its limits and large TH uncertainites
- Precision foreseen to be reached through ratios of cross sections.
- Key precision deliverables: top Yukawa coupling and Higgs trilinear coupling! FCC-ee and FCC-hh together are 2-3 times better than FCC-hh alone.

Ingredients

- FCC-ee measurement of the ttZ coupling ($e^+e^- \to t\bar{t}$ yields g_{ttZ})
- Measure the ratio ttH to ttZ at percent level!
- Then measure ratio HH to ttH



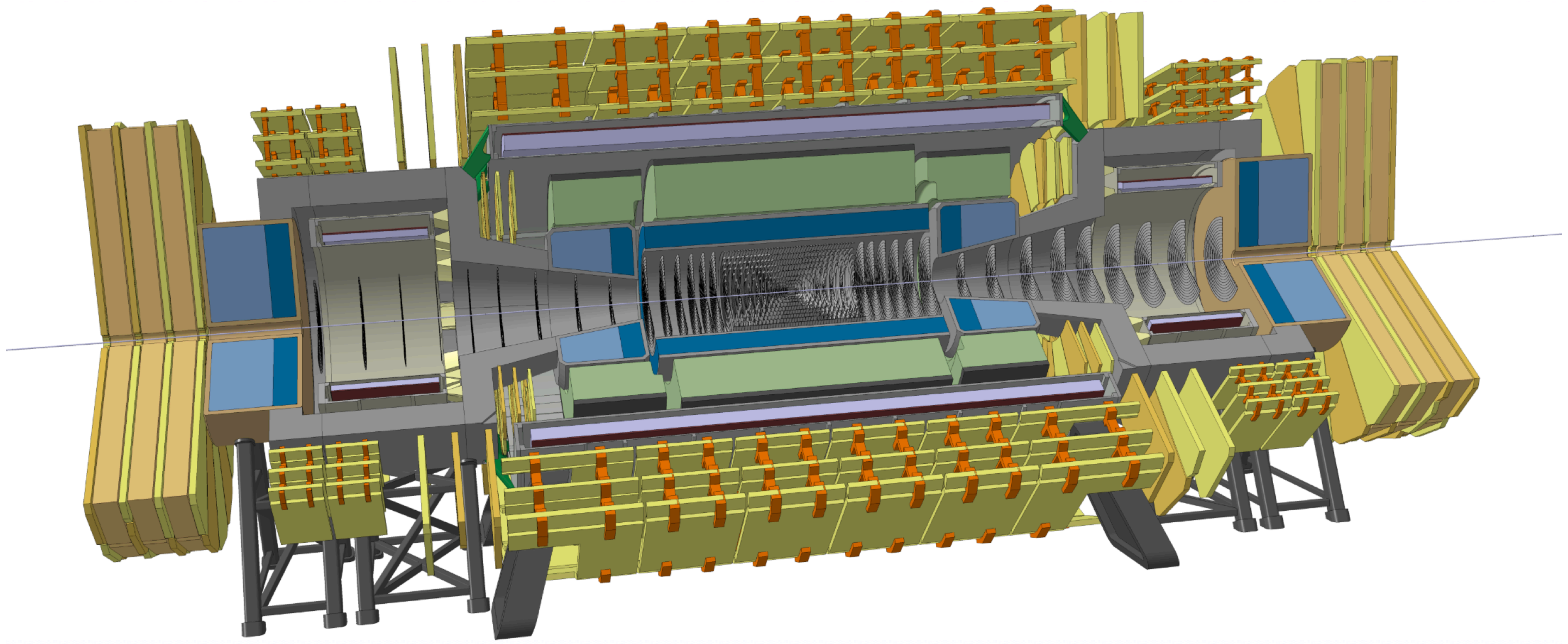
κ_t ~1%

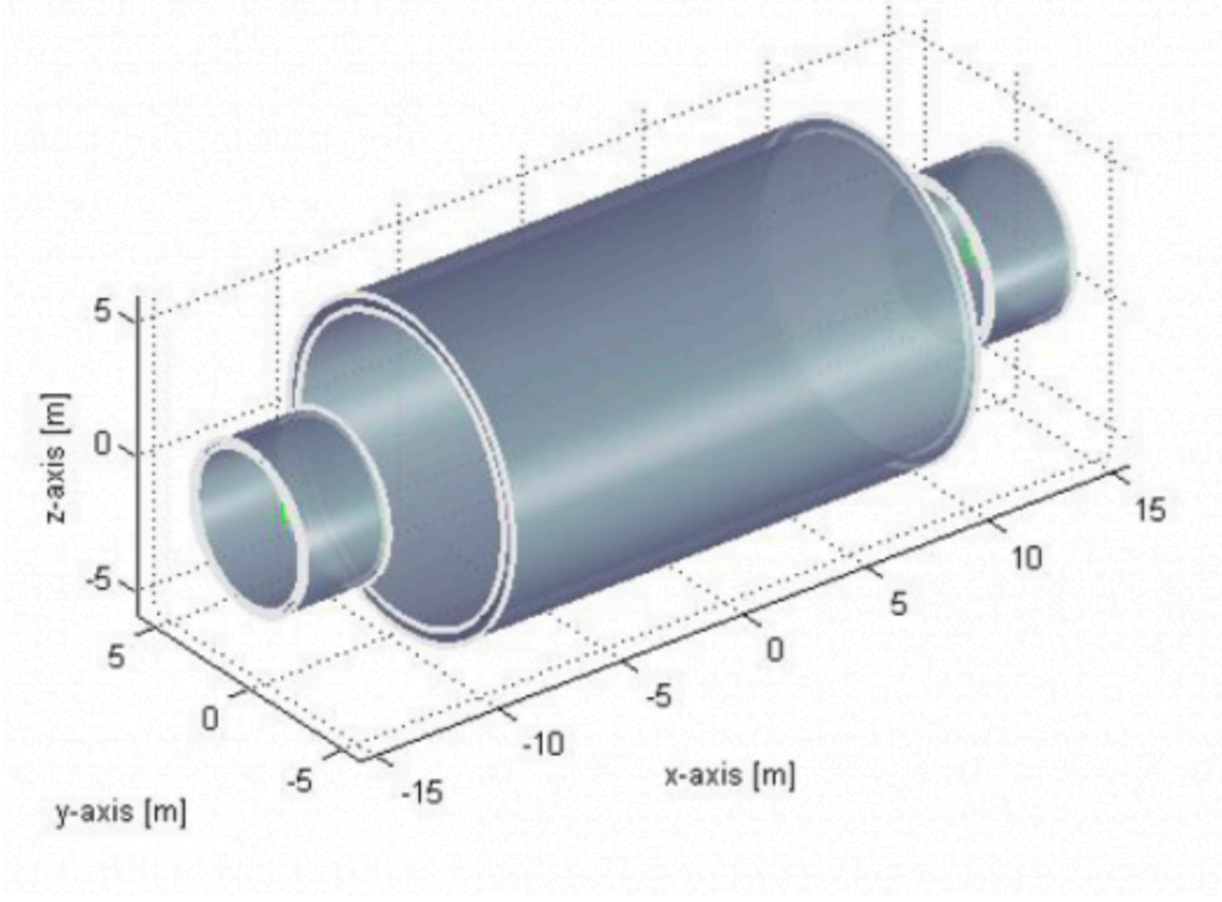


κ_λ ~5%

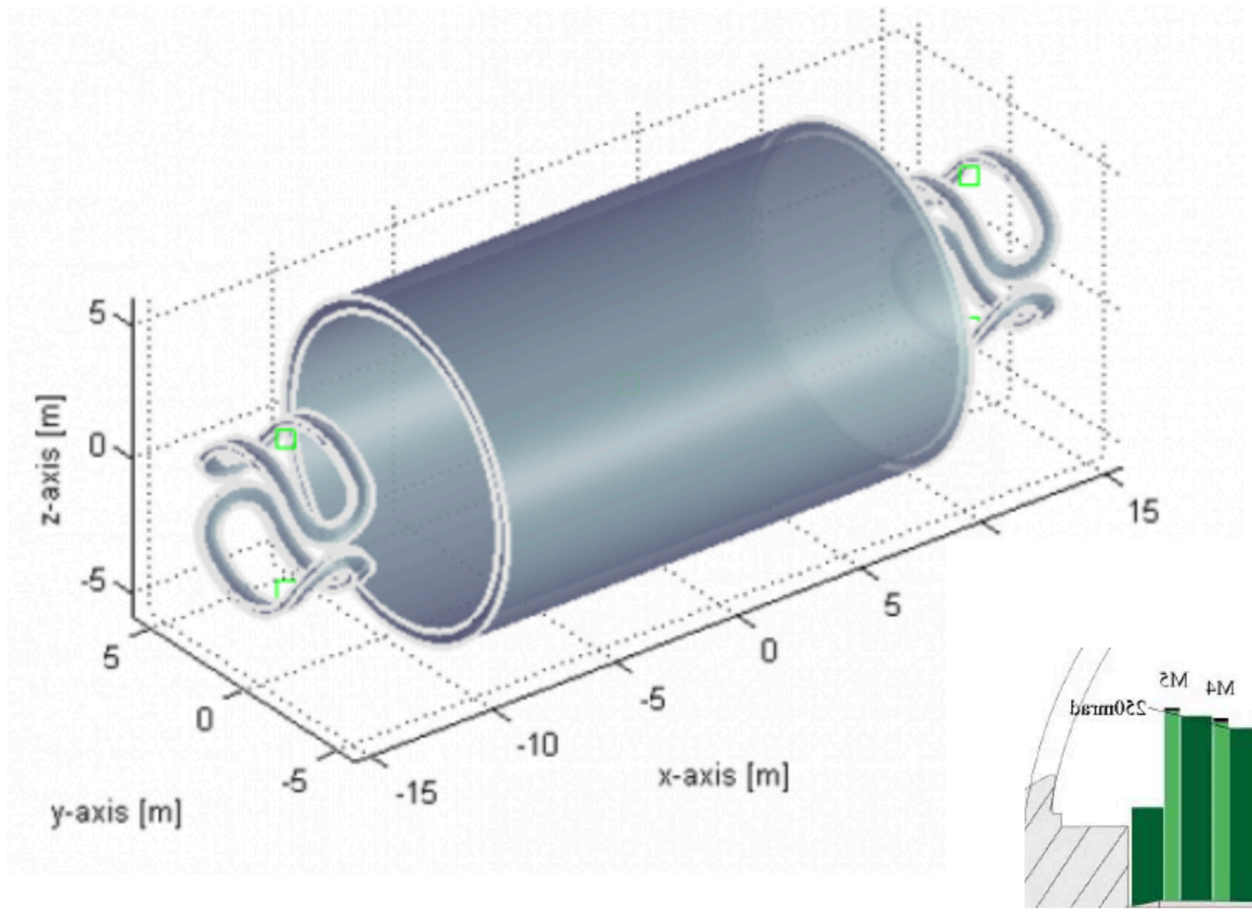
Hadron Collider Projects - Exploring the Multi-TeV scale

Dimensions commensurate (slightly larger) with current LHC experiments





Baseline



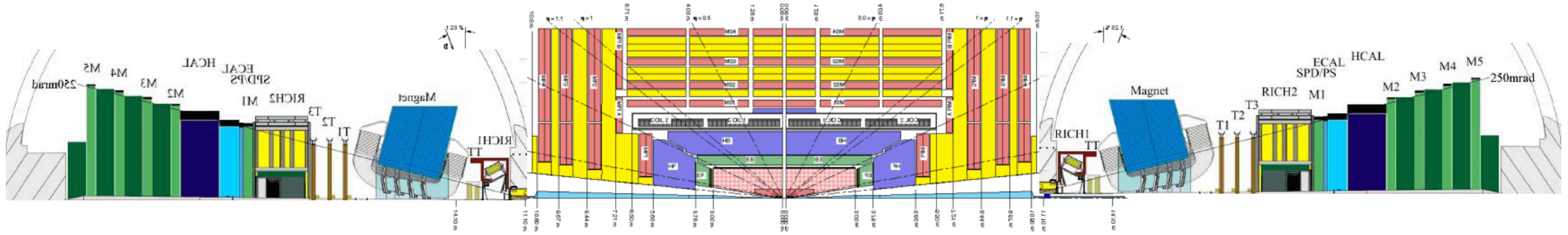
Alternative

FCC-hh key detector design challenges

- High luminosity - Extremely large PU, high occupancy and data rates, high trigger rates
- At FCC-hh Higgs produced up to rapidity of ~6.5 (up to 2.5 at LHC)
- Very high rates for triggering **Granularity** will be very important: decay product of a Z at 10 TeV separated by $\Delta R \sim 0.01$!!

Explore to improve on the resolution at high rapidity

Forward dipole magnet for high pseudo rapidity particles
Drawback: breaks the rotationally symmetric system…
Would be similar to a central CMS and two LHCbs in the forward directions!



Muon Collider Project - Exploring the Multi-TeV scale

Best of all worlds?

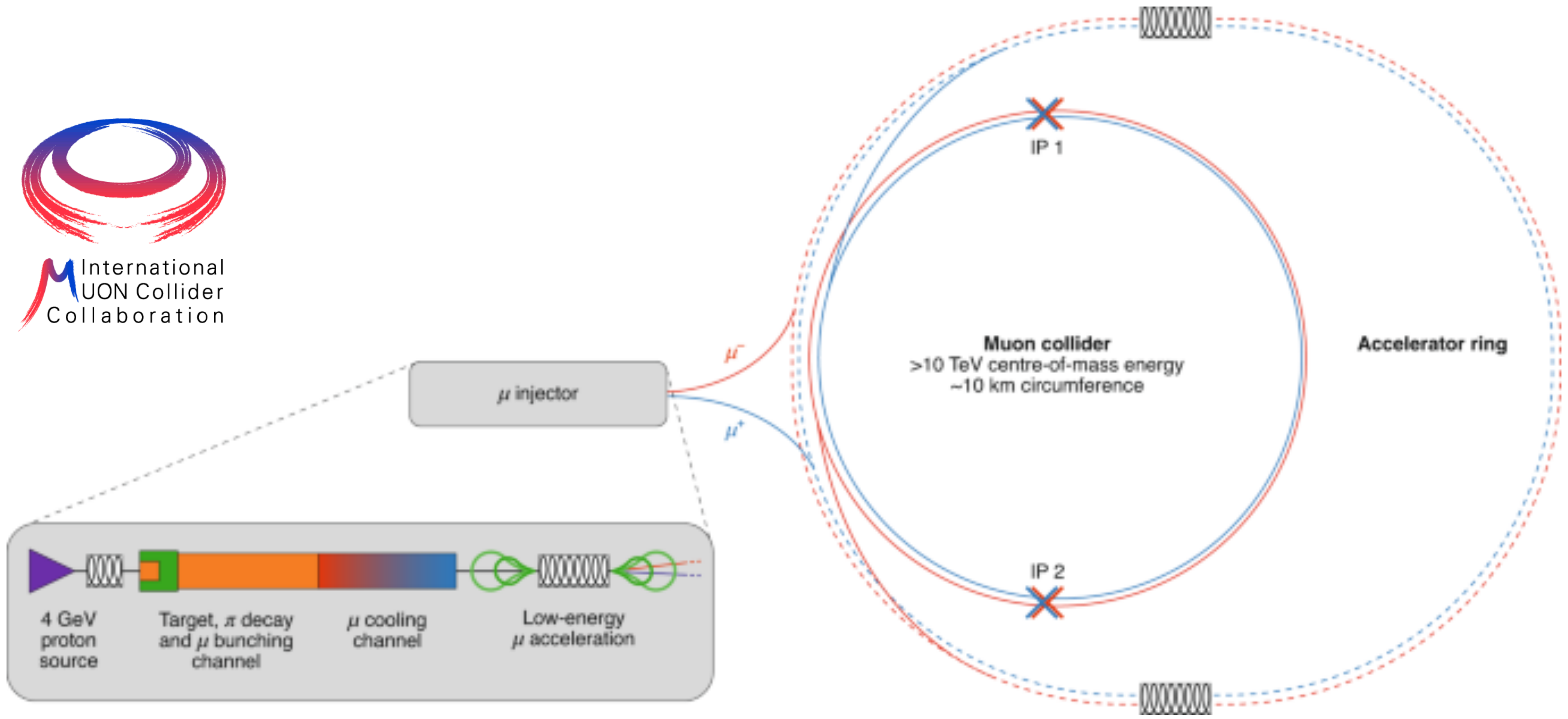
High energies, high luminosities with excellent lumi per MW ratio, (relatively) clean lepton collision events!

Mostly aimed at new physics searches in the Multi-TeV scale reach!

… incredibly challenging!

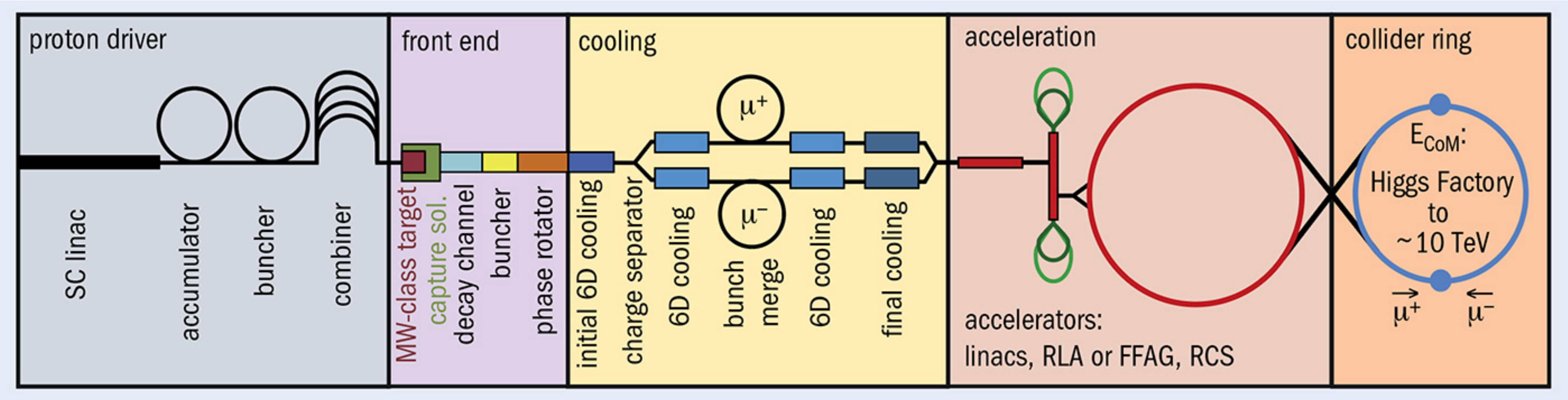
Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab−1 for 3, 10 and 14 TeV, **respectively**.

International
MUON Collider
Collaboration



MAP (Muon Accelerator Program)
Proton driven scheme

Reduction of the longitudinal and transverse emittance with a sequence of absorbers and RF cavities in a high magnetic field.

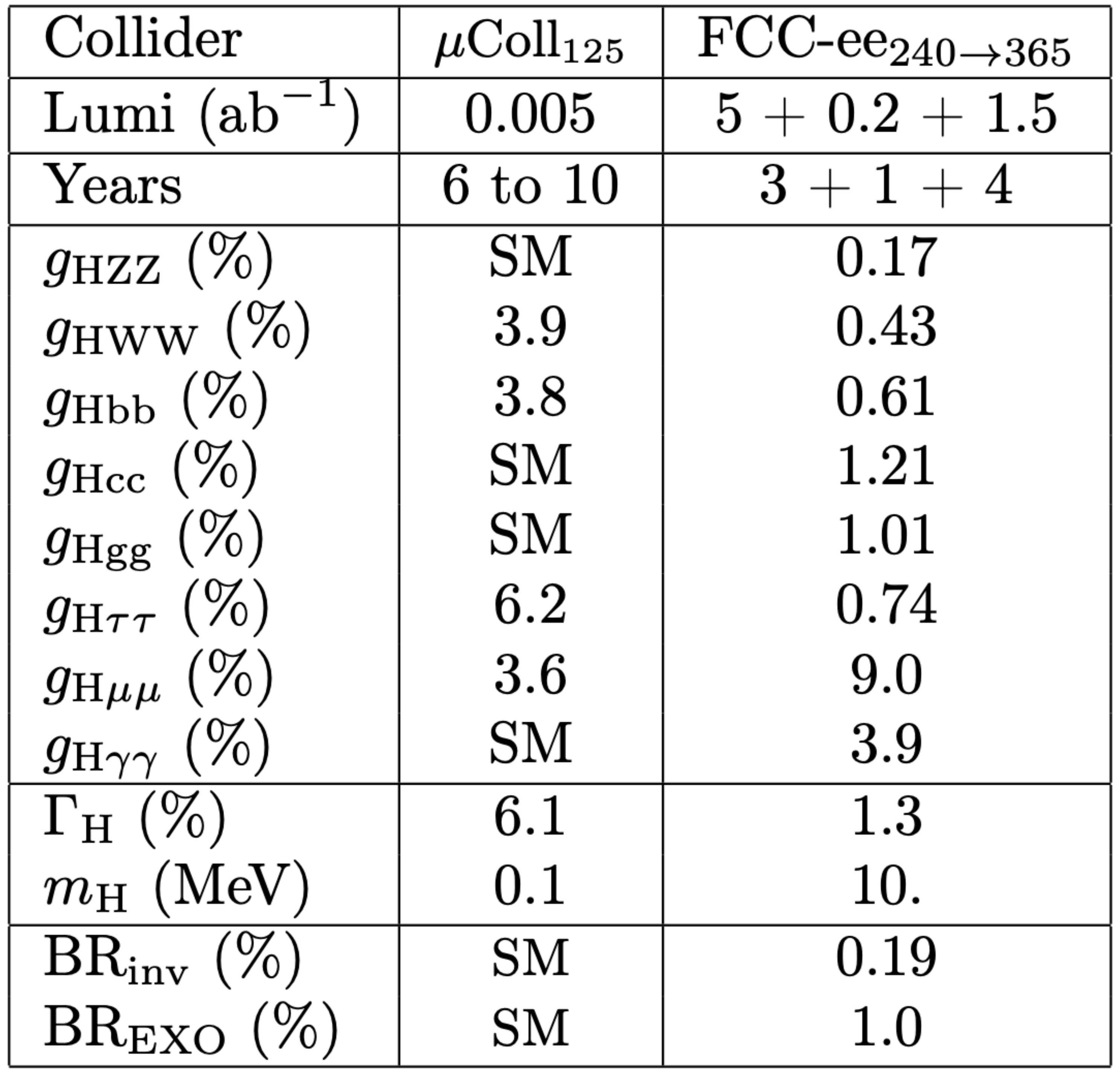


Muon Collider Project - Exploring the Multi-TeV scale

Muon collider as a Higgs Factory?

In principle could do everything as an e^+e^- collider with a much smaller ring! However the luminosity is estimated to be 2 orders of magnitude smaller at 240 GeV.

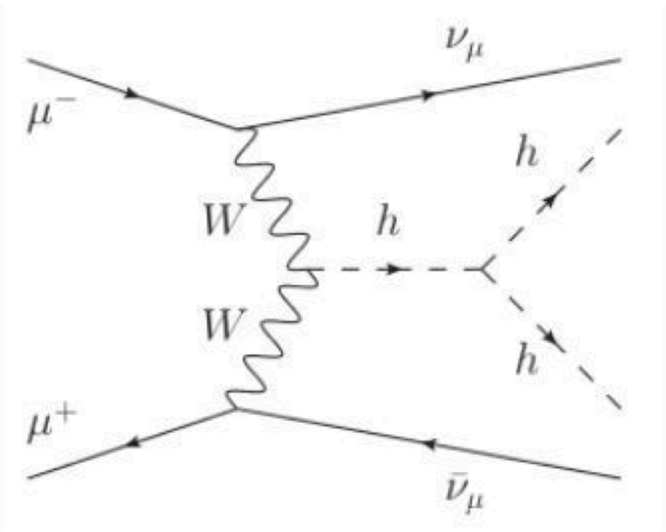
However at 125 GeV the s-channel production is 40,000 times larger (and a beam spread ~width).



Collider	μColl$_{125}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	0.005	5 + 0.2 + 1.5
Years	6 to 10	3 + 1 + 4
g_{HZZ} (%)	SM	0.17
g_{HWW} (%)	3.9	0.43
g_{Hbb} (%)	3.8	0.61
g_{Hcc} (%)	SM	1.21
g_{Hgg} (%)	SM	1.01
$g_{\mathrm{H}\tau\tau}$ (%)	6.2	0.74
$g_{\mathrm{H}\mu\mu}$ (%)	3.6	9.0
$g_{\mathrm{H}\gamma\gamma}$ (%)	SM	3.9
Γ_{H} (%)	6.1	1.3
m_{H} (MeV)	0.1	10.
BR$_{\mathrm{inv}}$ (%)	SM	0.19
BR$_{\mathrm{EXO}}$ (%)	SM	1.0

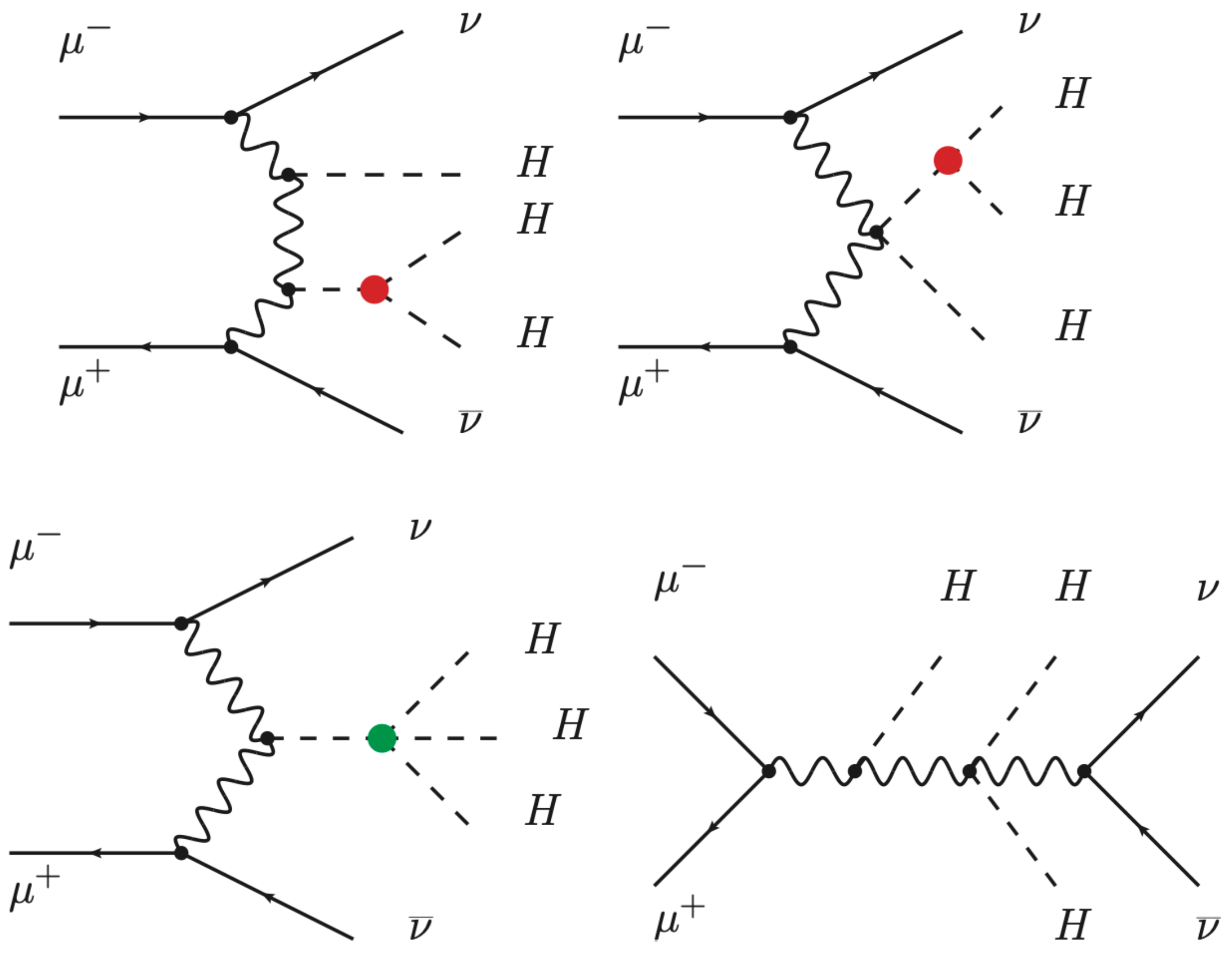
Muon Collider at 3 TeV

Notable result reach on trilinear coupling from di-Higgs production $\lambda_3 \sim 20\,\%$



Muon Collider at 14 TeV

Quartic couplings studies show (see paper)



Assuming $\lambda_3 = 1$ and $33\ ab^{-1}$ could reach **50%** precision of the Higgs boson quartic coupling.

Muon Collider Project - Exploring the Multi-TeV scale

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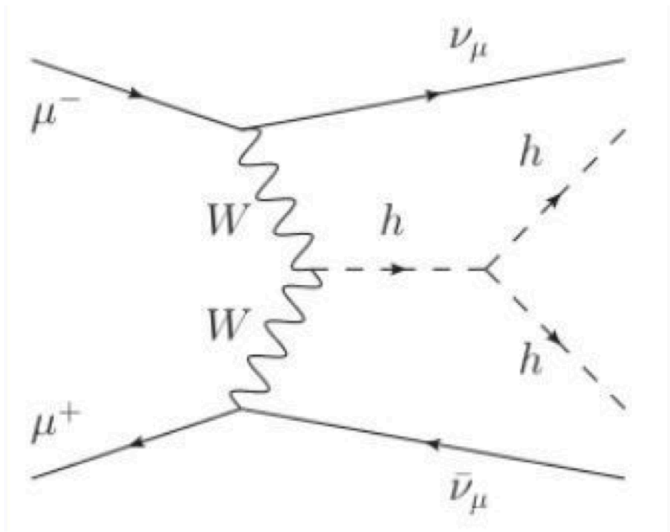
Muon Collider at 3 TeV

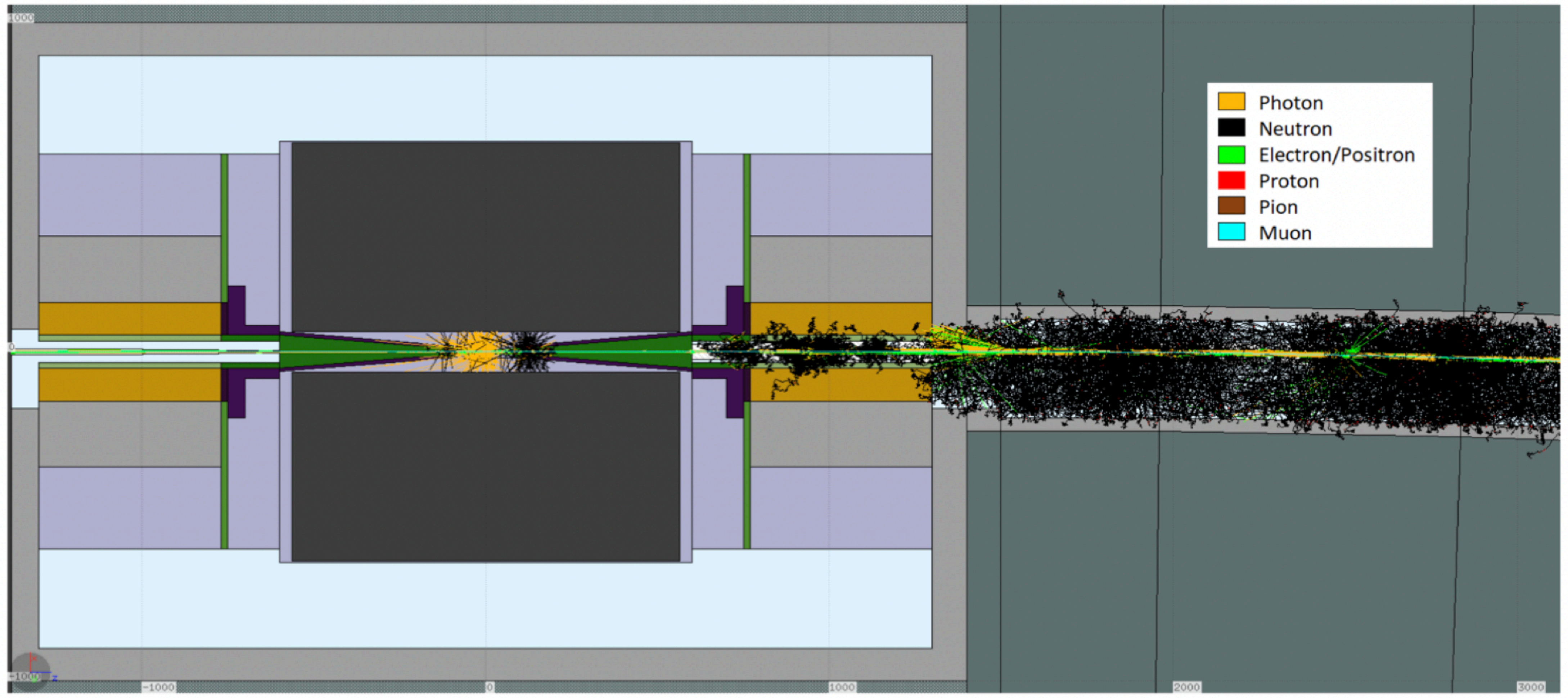


Notable result reach on trilinear coupling from di-Higgs production $\lambda_3 \sim 20\,\%$

Conceptual and design challenges

- High neutrino flux (requires mitigation above 3 TeV)
- Beam backgrounds challenge to detector design.
- Production, cooling and preservation of the muons!

Constant muon decays bring beam backgrounds, and radiation levels similar to LHC!



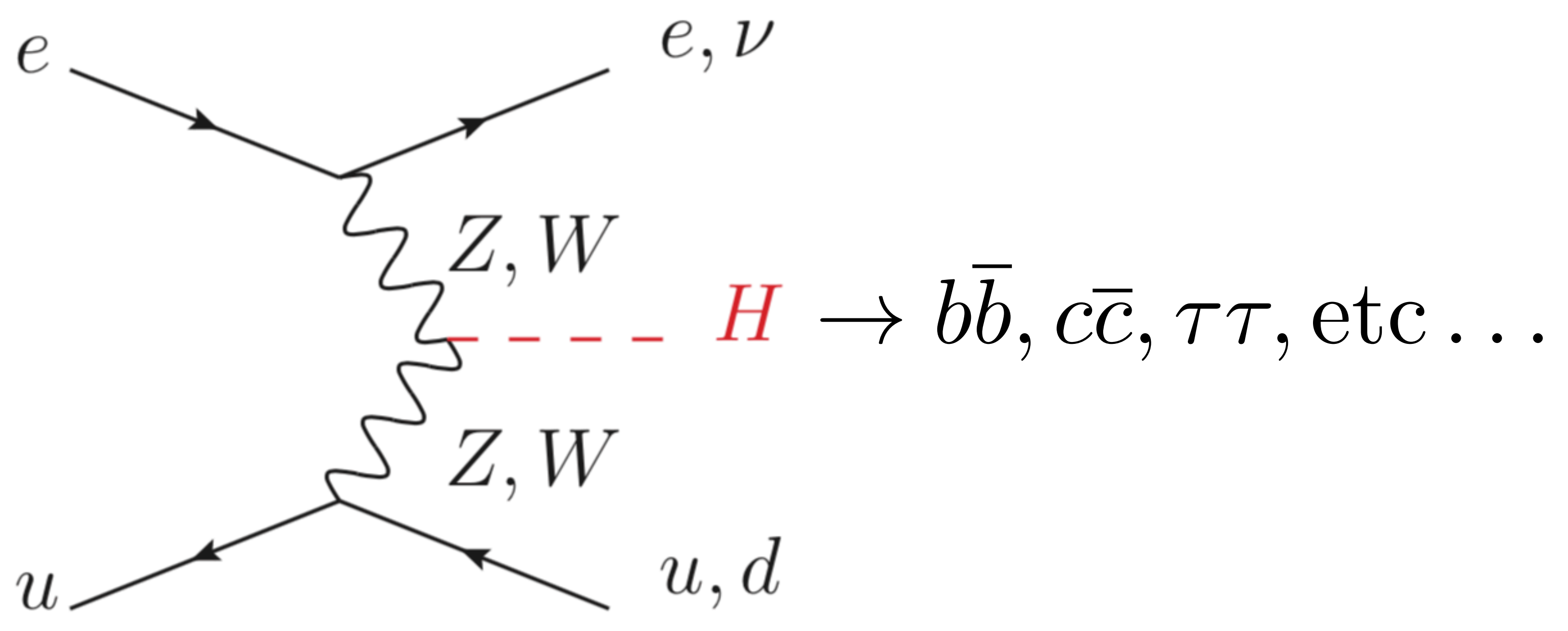
High Energy electron-proton Projects

The eh candidate machines

Project	**LHeC**	**FCC-eh**
Location	CERN	CERN
e energy	60 GeV	60 GeV
p energy	7 TeV	50 TeV
Lumi.	$0.8\ 10^{34}\ \mathrm{cm^{-2}s^{-1}}$	$1.5\ 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Primary program to measure proton PDFs, but also nice additional potential in Higgs physics

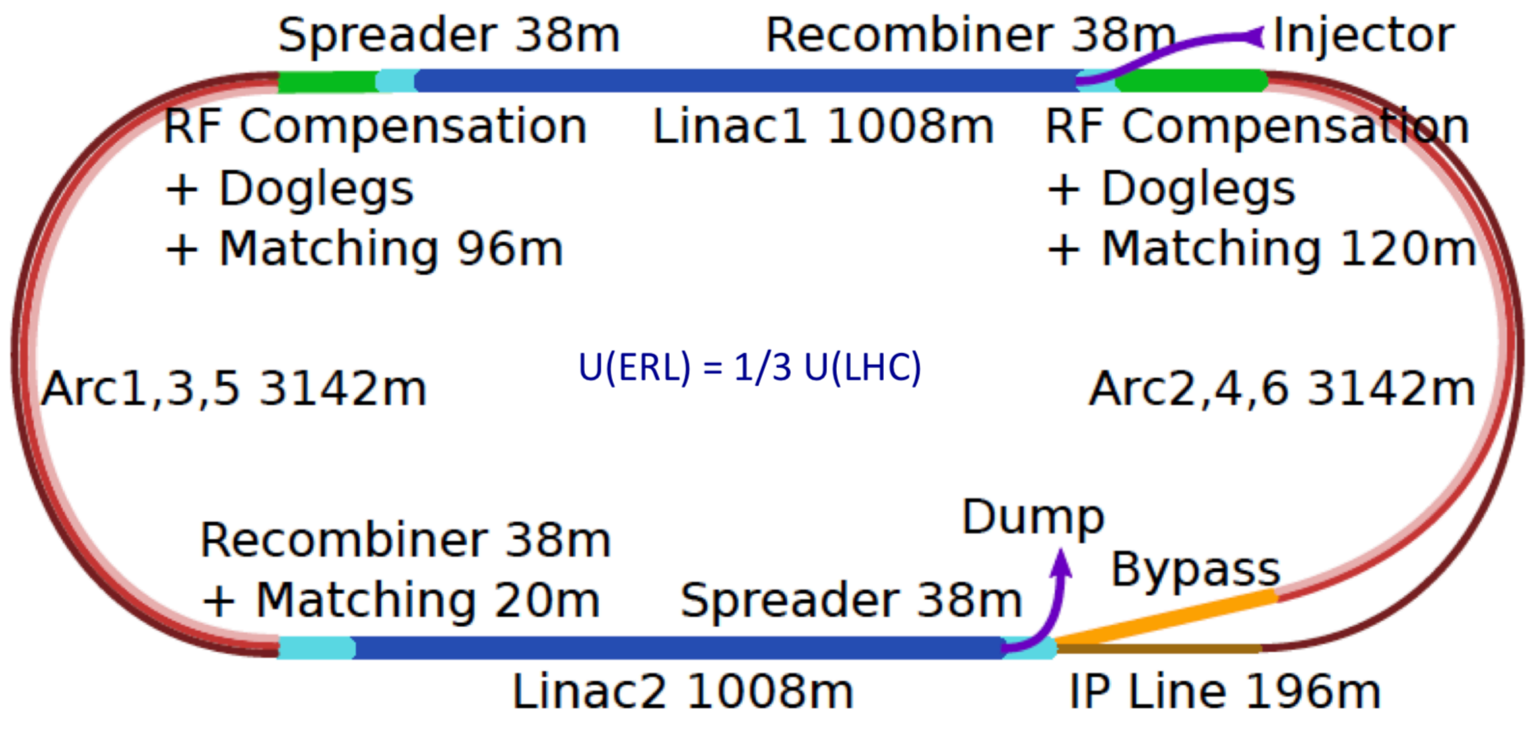
Main production process through vector boson fusion

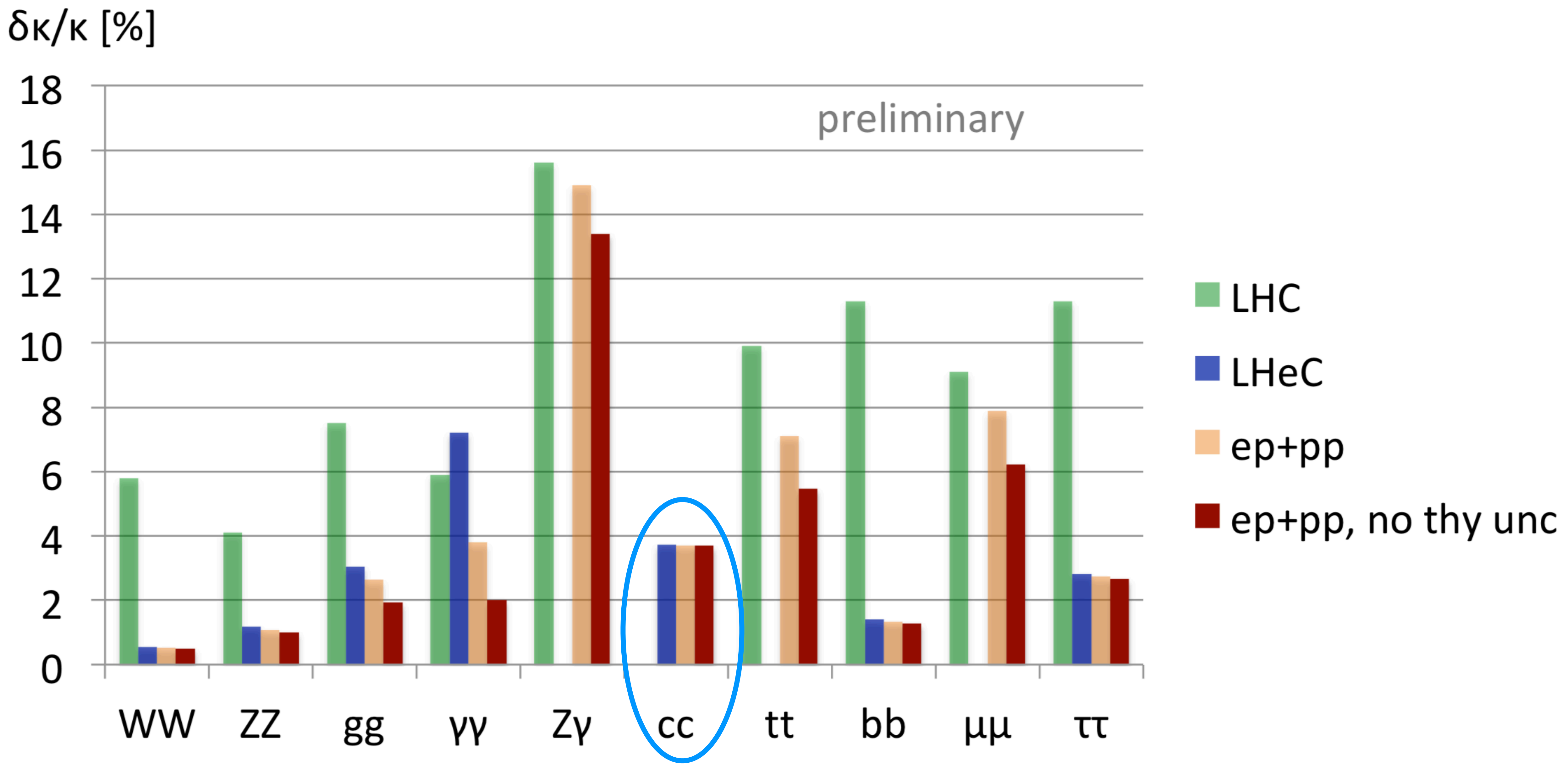


Much cleaner environment than pure hadron!

Good reach in the WW channel.

60 GeV Electron ERL added to LHC





Clean enough to make charm Yukawa at good precision and improvement in the b Yukawa as well w.r.t. HL-LHC.

Conclusions

- The Higgs boson is at the centre of a large number of fundamental questions, and its detailed study is key to answer these questions.

- The results obtained so far exceed very significantly the expectations at the start of the project (3 decades ago!).

- Higgs physics is therefore a vast experimental and theoretical research program providing essential **guaranteed deliverables** in the short term for the High Luminosity LHC, the medium term with an electron-positron collider and in the long term with a multi-TeV collider.

- Collider projects from the HL-LHC to Multi-TeV machines offer a physics program for the 21st century with immense opportunities in particular in Higgs physics.

Backup

Performance Achievements: Trigger

- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.

- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
    - Keeping Trigger thresholds at similar levels
    - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
    - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

Menus at LHC and for HL-LHC

Signature	Run 1	Run 2	HL-LHC
Single e (isolated)	25	27	22 / 27
Single photon	120	140	120*
HT	700	700	375 / 350
MET	150	200	200

From A. Sfyrla LHCP 2018

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

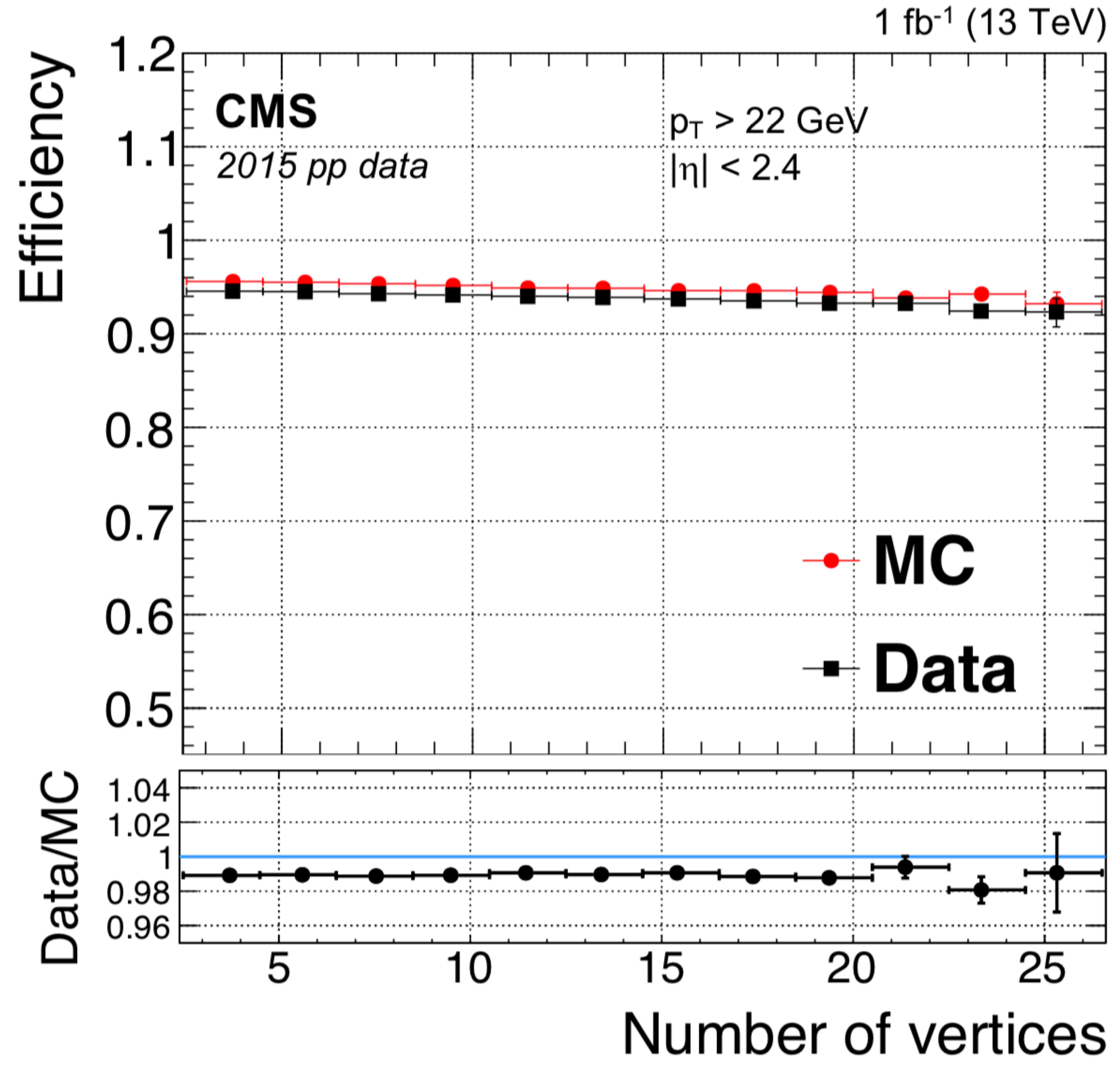
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

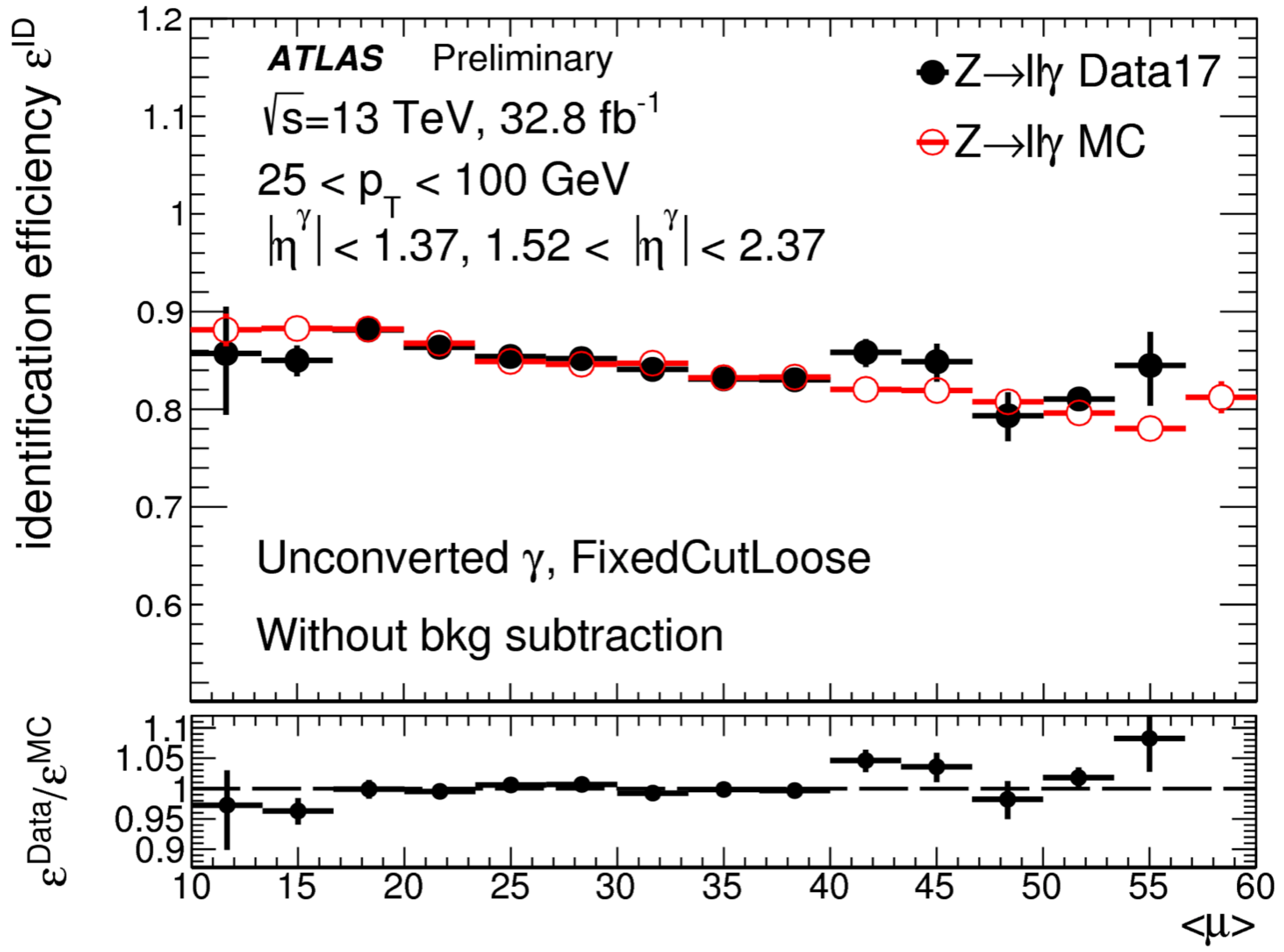
Taus

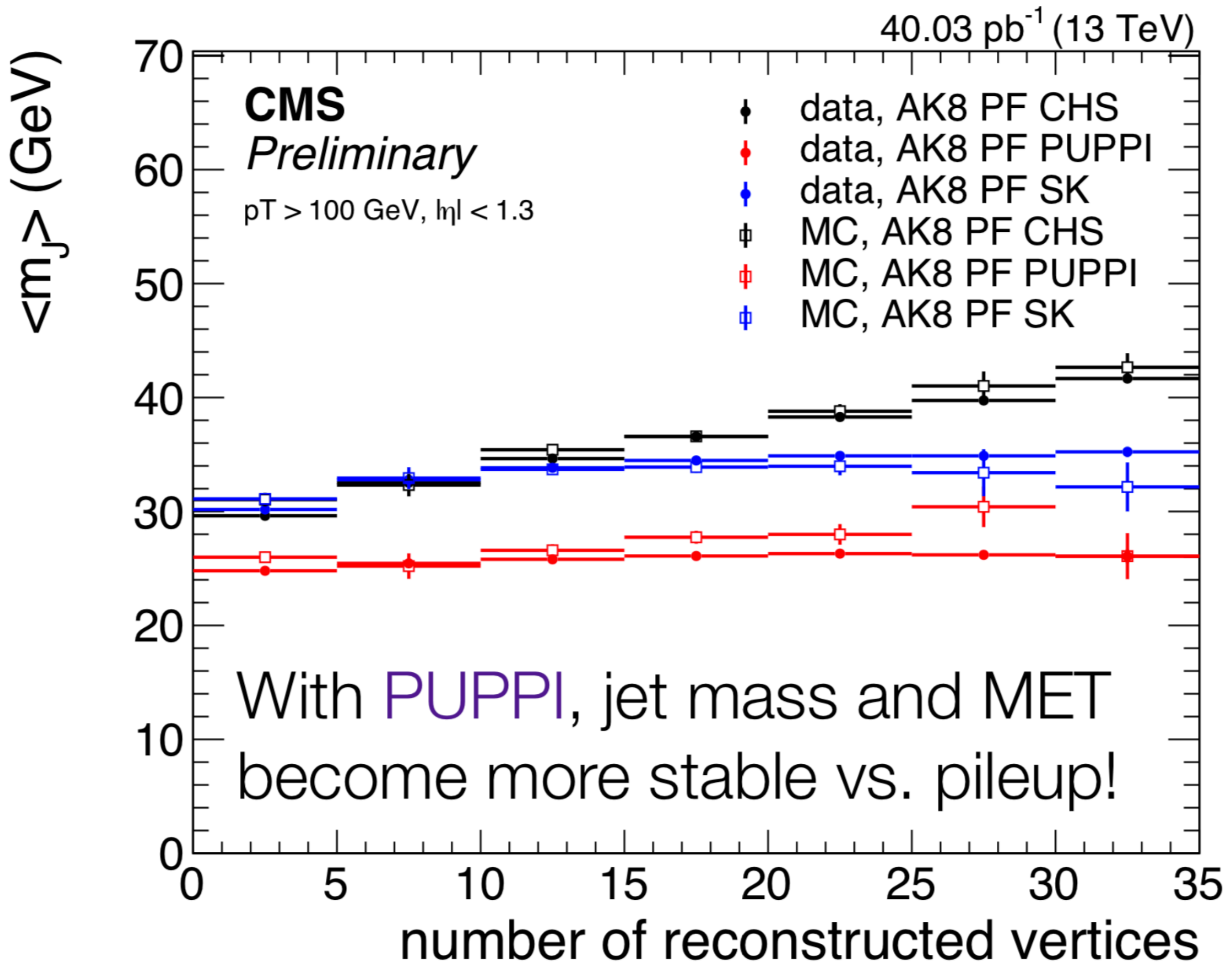
- BDT and RNN based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

B- and C-jets

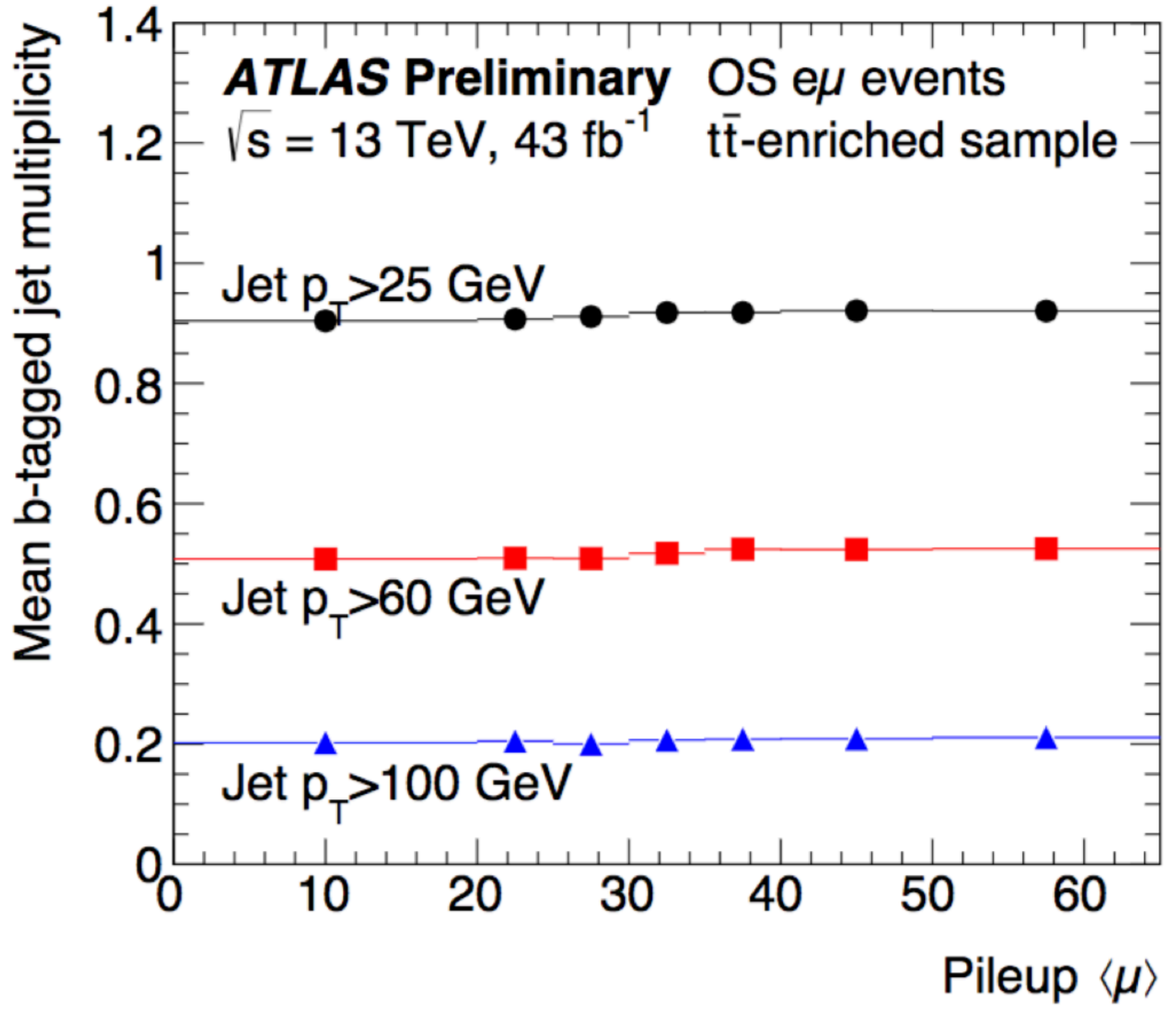
- In-situ calibration of b-tag efficiency (using top events and/ or diet events)
- DL techniques from low level variables bring significant improvements







With PUPPI, jet mass and MET become more stable vs. pileup!



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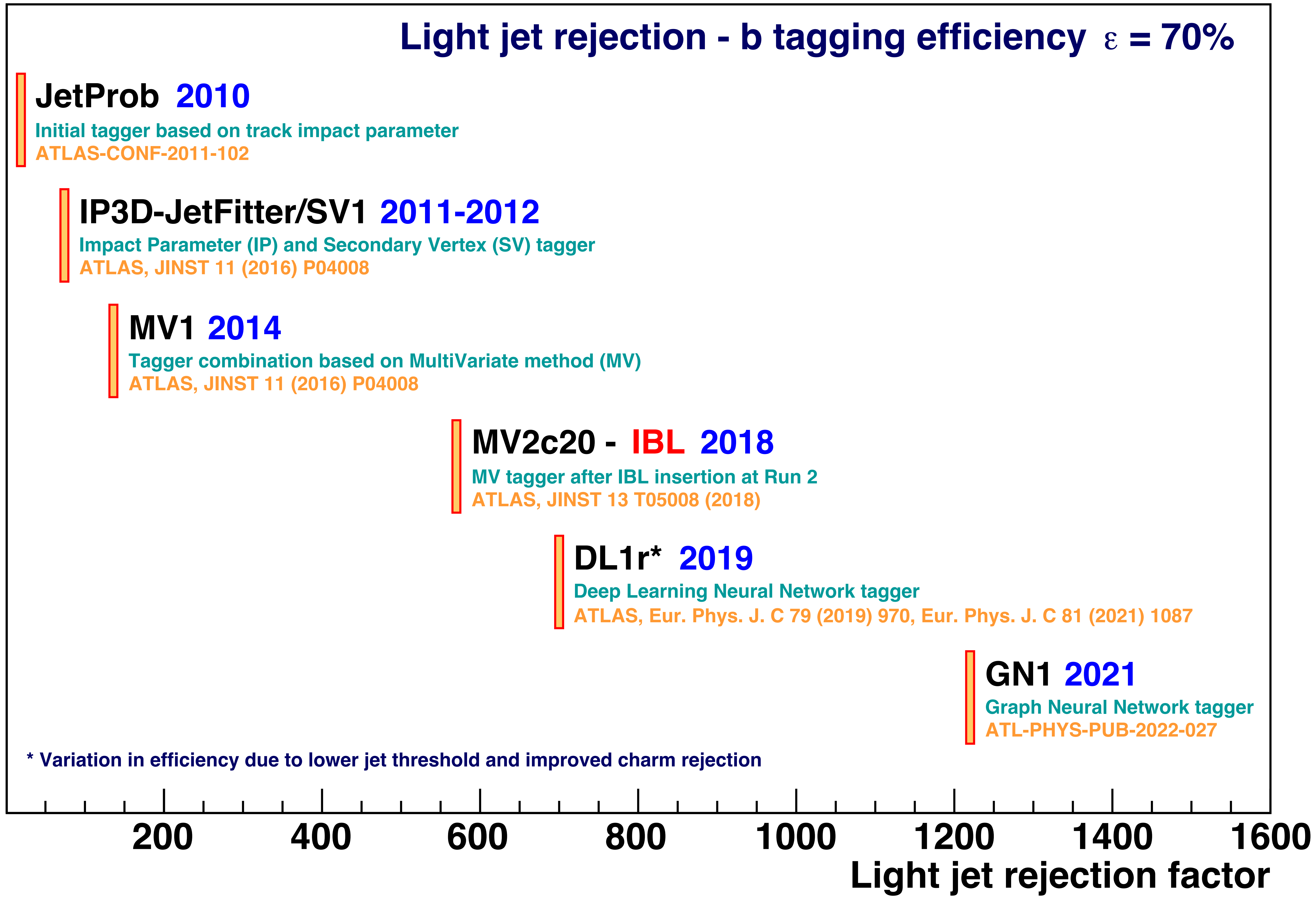

Reconstruction performance: Well calibrated, robust to PU and… well exceeding expectations!